Energy Aware Survivable Routing Approaches for Next Generation Networks Design

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G (N, L): A network topology consisting of a set of N nodes and a set of L links.

a : Network element, either be a node or a link.

l_a : The total traffic load of primary path of a.

l'_a: The total traffic load of backup path of a.

C_a: The capacity of a.

α: An arbitrary value in the range of 0 to 1 to preserve QoS, which is a configurable utilization threshold of network elements.

M: Constant value used in the big-M constraints. M is a "big" number (i.e., greater than twice the maximum nodes capacities).

T_i: The request traffics matrix. i is the index of the matrix.

p_{xy}^{sd}: Number of path requests from *s* to *d* which passes through link *(x, y)* in their primary path.

∂_{mn}^{sd}: Number of path requests from *s* to *d* which passes through link *(m, n)* in their backup path.

k_a: A binary variable. If k_a = 1, network element a is in working status.

s_a: A binary variable. It indicates whether a network element in sleeping mode or not. If s_a = 1, network element a is in sleeping state for backup protection. If s_a = 0, network element a is either in primary path or has no load at all.

$z1_a$: A binary variable. If $z1_a$ = 1, network element a adapts to the first working level of energy expenditure.

$z2_a$: A binary variable. If $z2_a$ = 1, network element a adapts to the second working level of energy expenditure.

$z3_a$: A binary variable. If $z3_a$ = 1, network element a adapts to the third working level of energy expenditure.

$z4_a$: A binary variable. If $z4_a$ = 1, network element a adapts to its maximum power.

E_a: The total energy consumption of network element a.

E_{ma}: The maximum energy consumption of network element a when it is turn on.

E_{0a}: The minimum energy consumption of network element a when it is turn on. It indicates the minimum power to maintain a network element in working status.

E_{sa}: The energy consumption of network element a when it is in sleeping mode. It represents the sleeping status' power consumption of a network element.

k_{L, T_i}: A binary variable. If k_{L, T_i} = 1, link L is used as a primary link by a connection request T_i. If k_{L, T_i} = 0, link L is not used as a primary link by a connection request T_i.

$k1_{L, T_i}$: A binary variable. If $k1_{L, T_i}$ = 1, link L is used as a backup link by a connection request T_i. If $k1_{L, T_i}$ = 0, link L is not used as a backup link by a connection request T_i.

$p0_{T_1, T_2}$: A binary variable. If $p0_{T_1, T_2}$ = 1, the primary paths of T_1 and T_2 have overlapped link, which means T_1 , T_2cannot share backup. If $p0_{T_1, T_2}$ = 0, the primary paths of T_1 and T_2 are disjointed, which means T_1 , T_2 may share backup capacity.

$p1_{L, T_1, T_2}$: A binary variable. If $p1_{L, T_1, T_2}$ = 1, the link L used as backup paths for both T_1 and T_2, which means T_1 , T_2 may share backup in L. On the other hand, if $p1_{L, T_1, T_2}$ = 0, the link L used as backup paths for either T_1 or T_2, and also may not be used as backup for T_1 and T_2. In this case, T_1 and T_2 cannot share backup resource in L.

$p2_{L, T_1, T_2}$: A binary variable. If $p2_{L, T_1, T_2}$ = 1, T_1 and T_2 can share backup in link L. If $p2_{L, T_1, T_2}$ = 0, T_1 and T_2 cannot share backup in link L.

C_{L, T_1, T_2}: The amount of backup capacity can be shared by T_1 and T_2 in link L.

Attestation of Authorship

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, no material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning.”

Signature of Candidate: ……………………………………………………

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Abstract

Currently, with the booming development of Next Generation Networks (NGNs), there is an urgent request for reducing energy in telecommunication networks due to its environmental impact and potential economic benefits. However, the most existing green networking approaches take no or less consideration on network survivability aspect. This thesis aims to tackle the trade-off problem between energy efficiency and network survivability.

In this thesis, we optimize this trade-off problem by using energy aware survivable routing approaches. This sort of trade-off problem falls in the class of capacitated multi-commodity minimum cost flow (CMCF) problems i.e., the problem in which multiple commodities have to be routed over a graph with some constraints. Generally speaking, this problem is also categorized as combinatorial optimization, which can be precisely modelled using Integer Linear Programming (ILP) formulation. The ILP is a mathematical method for determining the best feasible solution to achieve an optimal objective such as maximum profit or lowest cost by given the mathematical models for a list of requirements and constraints represented as linear relationships. Using ILP formulas, we propose three energy aware survivable routing models, which are Energy Aware Backup Protection 1+1 (EABP 1+1), Energy Aware Backup Protection 1:1 (EABP 1:1), Energy Aware Shared Backup Protection (EASBP). From energy saving aspect, we integrate several energy efficient approaches into them, such as energy aware routing, sleeping mode, and energy consumption rating strategies. For network survivability concern, EABP 1+1, EABP 1:1, and EASBP are embedded with 1+1 backup protection, 1:1 backup protection, and shared backup protection respectively.

Moreover, for performance comparison, the three models have been implemented in IBM ILOG CPLEX Optimization Studio and solved by CPLEX 11.1 Solver. Moreover, since the CPLEX Optimization Studio can only produce theoretical results, we have developed and integrated the three energy aware survivable routing models into TOTEM (TOolbox for Traffic Engineering Methods) network simulator for better visualization.

We have conducted extensive case studies to validate these three models. The most energy efficient model – EABP 1:1 has been found, it could save up to 90% of energy consumption compared with the worst-case multi-commodity flow (MCF) algorithm, due to the combinational use of energy aware routing, sleeping mode strategies and energy consumption rating. In addition, the sleeping mode is an effective approach to reduce energy cost, and EABP 1:1 can save up to half energy usage than EABP 1+1 by introducing sleeping mode. However these two models consume a significant amount of capacity for network survivability purpose. Therefore EASBP has been proposed and the numerical results have confirmed that it is the best solution to tackle the trade-off problem between energy reduction and network survivability. This model consumes significantly less capacity with a small sacrifice on energy expenditure, especially under the condition of large traffic demands flowing in network.

Glossary

AMPL:	A Mathematical Programming Language
CMCF:	commodity minimum cost flow
EABP 1+1:	Energy Aware 1+1 Backup Protection
EABP 1:1:	Energy Aware 1:1 Backup Protection
EASBP:	Energy Aware Shared Backup Protection
EAR:	Energy Aware Routing
GHG:	Green House Gases
ILP:	Integer Linear Programming
ISDN:	Integrated Services Digital Network
MCF:	multi-commodity flow
NCP:	Network Connectivity Proxy
NGNs:	next generation networks
NIC:	Network Interface Cards
OPL:	Optimization Programming Language
QoS:	Quality of Service
PSTN:	Public Switched Telephone Network
TOTEM:	TOolbox for Traffic Engineering Methods

Chapter 1

Introduction

Nowadays, along with the rapid development of Internet, telephone, mobile, and Community Antenna Television (CATV) services, an “information era” has come. Naturally, the next generation networks (NGNs) [1] becomes a promising trend, which integrates the Data/IP networks, Public Switched Telephone Network (PSTN), Integrated Services Digital Network (ISDN), cellular networks, and CATV networks into one all over IP platform. There are three main advantages of NGNs. The first is to suit the users’ increasing demand for integrated service. The second is to reduce the operational expenditure of telecom companies. Lastly, it is to avoid constructing repeated network infrastructures for different services. However, as the services continue to grow dramatically, the power consumption of NGNs is rising at a considerable speed, which seriously increases the operational expenditure as well as the greenhouse gas emission to the environment. As for internet alone, the power consumption of it today is around 1-2% of the total energy consumption in broadband enabled countries and it is expected to reach higher values with the growing bandwidth demand [2].

For the reduction of unnecessary energy consumption in NGNs, the concept of green networking has been advocated, which refers to embedding energy-awareness in the design, in the devices and in the protocols of networks [3]. In this thesis, we mainly apply energy aware routing and also sleeping mode approaches to achieve energy saving of telecommunication networks. The energy aware routing [4] generally aims at aggregating traffic flows over a subset of the network devices and links, then allowing other unloaded links and devices to sleep or to be switched off. The existing green solutions of energy aware routing normally sacrifice the network survivability performance so as to achieve the energy reduction. The survivability is defined as the network’s ability to recover from a failure. It should not be neglected to solely pursue the energy efficient NGNs since a single fibre cut would lead to a huge loss of data. While implementing network survivable mechanisms such as backup protection or restoration certainly will increase the energy usage because more network components should be provided. Therefore, there is a challenging trade-off problem between energy reduction and network survivability.

This thesis focuses on tackling the trade-off problem for energy aware survivable NGNs design. In-depth descriptions of three energy aware survivable routing algorithms are provided and their Integer Linear Programming (ILP) models [5] are presented. Then the three routing algorithms are implemented in IBM ILOG CPLEX Optimization studio [6] and their ILP formulations are solved by the CPLEX 11.1 Solver [7]. By conducting the extensive case studies, the performance of these three routing algorithms are extensively compared and analysed. Moreover, to visualize the theoretical numerical results, we have developed and embed the three energy aware survivable routing models into a network simulator, i.e., TOolbox for Traffic Engineering Methods (TOTEM) [8].

In this chapter, firstly the section 1.1 gives a background on the trend and potential of energy saving approaches for Next Generation Networks (NGNs). Then, in section 1.2, we have identified the research problems and also present our motivations to tackle the trade-off problems between energy reduction and network survivability. Following that, the section 1.3 summarizes our contributions. Lastly, an overview of the structure of this thesis has been given in the section 1.4.

1.1 Background

In the coming information era, the information can be obtained through Internet, telephone, mobile and television. The networks of these above four media are independent, and may operate by different companies. Therefore, these are two main concerns are raised. Firstly, it is difficult to provide integrated service to subscribers, which will allow them access to different media conveniently. The second concern is that it cannot avoid the repeated network infrastructures, which will lead to unnecessary operational expenditure, and resource and cost waste. Therefore, to realize the users' increasing demand for integrated service and to reduce the operational expenditure of telecom companies, the next generation networks has been proposed and developed. The NGNs intend to integrate the Data/IP networks, PSTN, ISDN, cellular networks, and CATV networks into one universe all-over-IP communication platform, which can host and transport various information and services such as voice, data, video etc. While the power consumption of the NGNs has recently become a key challenge because of these significant growing on traffic demands. In particular, the actions to improve energy-efficiency of telecommunication networks are imperative. For this purpose, the professionals advocate green networking which is related to embedding energy-awareness in the network infrastructure design, in the devices such as routers and transmission lines as well as in the protocols of networks so as to reduce energy consumption.

In recent years, the requests for green networking in telecommunication networks have become increasingly important due to its environmental impacts [9-10] and potential economic benefits [11-12]. Firstly, the various studies such as [13-15], have started highlighting the devastating effects of massive Green House Gases (GHG) emissions and their consequences on the climate change. It is reported that the volume of GHG emissions produced by the telecommunication sector alone accounts for approximately 2% of the total man-made emissions [16]. Moreover, considering the rapid development of telecommunication services, the situation could become even worse in the future [17-18]. As the ITU-T Technology Watch Reports [19] points out, the energy usage of telecommunication sector will grow over time steadily, and therefore it is important that the industry takes solid steps to curb and ultimately reduce its carbon emission as earlier as possible. Secondly, as far as the economic aspects are concerned, energy-efficient network could help telecom companies to reduce the operational expenditures. Normally, telecom companies spend a large amount of money on energy consumption due to its huge scale of network infrastructure. The paper [20] has reported that the power consumption of telecommunication networks is not negligible. Taking Telecom New Zealand limited as an example, as shown in its official website [21], it is one of the top 15 electricity users in New Zealand, and approximately 85% of its energy consumptions relate to the running the network. Furthermore, the website also indicates the trend of energy demand was increasing steadily by about 4% every year, from 194.3 Giga-watt Hours in 2005 to 233.4 Giga-watt Hours in 2009. Hence, it is urgent to apply energy saving technologies for greening networks.

However, the architectures of the existing telecommunication networks are often designed to endure peak loads and degraded conditions, which leave a large space for energy savings since they are under-utilized in normal operations [22] for most of time.

Besides, the current network operational approach is also energy unaware, e.g., balancing the traffic as evenly as possible on the network links [23], or minimizing the bandwidth and maximizing the shareability of backup wavelengths [24], which do not consider network resource e.g., nodes and links operational energy consumption. Therefore, by considering all the current research studies above, it is urgent to apply energy efficient approaches into our telecommunication network design. In recent years, we have seen great progress in green networking technologies that enable telecommunication systems to reduce energy expenditure from different network layers such as adaptive link rate applied in Data Link layer [25], Interface Proxying used in Application and Network layers [26], and also the Energy Aware Application applied in Transport layer [27].

1.2 Motivation

The green technology is improving rapidly in recent years' research studies, while the current green approaches take little consideration about the network survivability aspect. The definition of network survivability [28] is the capability of a system to fulfil its mission, in a timely manner, in the presence of threats such as attacks or large-scale natural disasters. In other words, network survivability refers to that when local failures happen, such as fibre cuts, key components malfunction, or router hardware/software failures, the global information carrying ability of the network should not be jeopardized [4]. The popular mechanisms to increase network survivability are protection mechanism, and device utilization restriction.

The protection mechanism [59] is using extra redundancy resources to protect critical network components so as to guarantee the network services upon failures. When the primary path fails, the backup path can be used to resume the services immediately so that the quality of service would not be influenced. Moreover, the device utilization restriction is to limit the usage level of network devices. In the real world, the network operators set a threshold [50] as common practice to limit the load of the devices to enforce Quality of Service (QoS) and robustness in their networks.

However, applying network survivable approaches lessen the potentials of energy saving in green networks due to the nature of network survivability strategy which is to provide extra backup resources. Our motivation is to study the trade-off problems between energy reduction and network survivability. From saving energy aspect, firstly, we apply energy aware routing, to aggregating traffic flows over a subset of the network devices and links. Then those non-working nodes and links will be switched into sleeping mode. In addition, the energy consumption of network elements is configured as several energy levels according to the volumes of its actual traffic load. For guaranteeing the network survivability requirements, we introduce the protection mechanisms into the routing algorithms.

Overall, in this thesis we are studying the trade-off optimization problems between network energy reduction and network survivability by applying energy aware routing approach, sleeping mode, energy consumption rating, as well as protection mechanisms.

1.3 Contributions

In this thesis, we have proposed three energy aware survivable routing algorithms, which is not only considering the energy reduction, but also taking network survivability into account. Our first contribution is to model the trade-off optimization problem between energy efficiency and network survivability, and also develop the Integer Linear Programming (ILP) formulations for the three routing algorithms. We name the three models as Energy Aware 1+1 Backup Protection (EABP 1+1), Energy Aware 1:1 Backup Protection (EABP 1:1) and Energy Aware Shared Backup Protection (EASBP). Energy consumption rating strategy is applied to them, which makes the energy expenditure relevant to its actual traffic loads. In addition, EABP 1:1 and EASBP have sleeping mode, which is expected to make further reduction on energy cost. What’s more, three protection mechanisms are embedded in each of them for enhancing the network survivability.

The second contribution is to implement the three energy aware survivable routing models in the IBM ILOG CPLEX Optimization studio and they are solved by the CPLEX 11.1 Solver. By conducting extensive case studies, the performances of our routing algorithms are comprehensively studied and compared. The results show that EASBP could be the best approach to tackle the trade-off between energy reduction and network survivability. This model consumes significantly less capacity but a small increase in energy expenditure, especially under the condition of large traffic demands.

Furthermore, for visualizing the theoretical results, we have developed and embedded the three models into a network simulator TOolbox for Traffic Engineering Methods (TOTEM). By modifying its core files, we changed TOTEM's drop-down menu list and GUI interfaces. What's more, we have integrated the three energy aware survivable routing algorithms into TOTEM function.

1.4 Thesis Outline

The objective of this thesis is to investigate and study the trade-off problem between energy saving and network survivability. It focuses on achieving energy reduction while still maintaining network resilience for designing next generation networks. Our main contributions are to propose three energy aware survivable routing algorithms using ILP formulas, and then compare their performance in IBM ILOG CPLEX Optimization studio. In addition, the three models are simulated and studied in TOTEM.

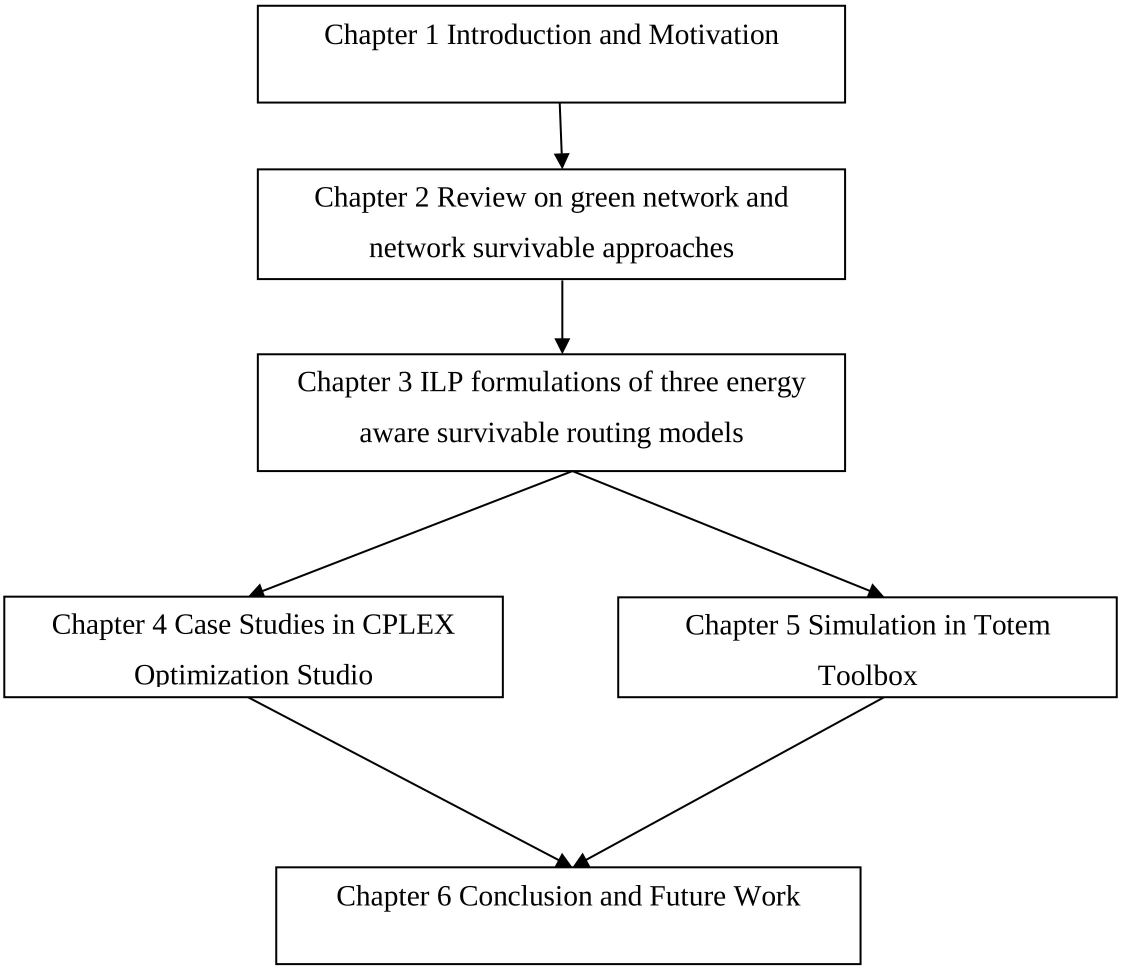


Figure 1.1 Thesis outline

The thesis's structure is depicted in Figure 1.1 above. The remainder of this thesis contains an introduction of relevant background knowledge, followed by benchmarking studies, ILP model descriptions and comprehensive analyses and discussion of three energy aware survivable routing models. The chapters of the thesis are organized as follows:

Chapter 2 firstly reviews the state of art of green networking researches. Then we present an introduction to the methods which are being applied into our new routing algorithms for achieving energy reduction and network survivability, such as energy aware routing, sleeping mode, energy consumption rating strategies, and protection mechanisms.

Chapter 3 introduces the background knowledge on Integer Linear Programming (ILP) modelling. Then we present our new proposed formulations for the three energy aware survivable routing models: Energy Aware 1+1 Backup Protection (EABP 1+1), Energy Aware 1:1 Backup Protection (EABP 1:1) and Energy Aware Shared Backup Protection (EASBP).

Chapter 4 we have conducted case studies on two referenced network topologies to validate the new routing algorithms. By using OPL+CPLEX optimization studio tool, the numerical results of their performances are collected and analyzed. Then the performance of the three models is compared in terms of their energy consumption, capacity utilization and network components such as nodes and links' utilization status such as in working, sleeping or being switched off. The results show that the Energy Aware Shared Backup Protection (EASBP) model could be a promising solution for the trade-off problem between energy consumption and network survivability. It consumes significantly less capacity but a small sacrifice in energy expenditure, especially under the condition of large traffic demands.

Chapter 5 presents how we develop the current TOTEM to integrate our new three energy aware survivable routing models in detail. The simulation results again has confirmed that EASBP model has significant advantage both on minimizing network elements' utilization and capacity usage, which is also can be visualized better.

Chapter 6 summarizes the main contributions of this dissertation as well as explains the limitations of the research work presented. We also suggest some possible directions for future research such as taking other network QoS metrics into consideration i.e. delay, control data, and further research on the relationship among our models, network topology, and traffic demands.

Chapter 2

Energy Aware and Survivable Routing Approaches

In this chapter, we firstly review the state of art approaches in green networking area. Then, from energy saving aspect, we introduce the green techniques applied into our three energy aware survivable routing models. Lastly, from network survivability perspective, we present three backup protection schemes, which enhance the robustness of our models.

The remainder of this chapter is organized as follows. First, the research studies on the latest mechanisms of green networking are reviewed. Then, several specific energy saving approaches are discussed in detail, such as energy aware routing, sleeping mode, and energy consumption rating strategies. In addition, we discuss the network survivability aspect and also compare several different protection mechanisms.

2.1 Background on Green Networking

The reduction of energy consumption has become a key issue for telecommunication industries, because of the economical and environmental reasons. This demand has a strong influence on electronics designers, the information and communication technology sector, and more specifically the networking field. Currently, networking infrastructure involves high-performance and high-availability machines, which require a large amount of power expenditures to sustain their operation. However, these machines are organized in a redundant architecture, often designed to endure peak load and degraded conditions, therefore most of the time they are underutilized in normal operation, which leaving a large room for energy savings.

In addition, the consciousness of environmental problems tied to Green House Gases (GHG) has increased in recent years. All around the world, various studies started highlighting the devastating effects of massive GHG emissions and their consequences on climate change. According to a report [12] published by the European Union, a decrease in emission volume of 15%–30% is required before year 2020 to keep the global temperature increase below 2℃. The telecommunication sector produced approximately 2% of the total man-made GHG emissions [16], and considering the rapid development of the industry, this situation could be even worse.

The green networking refers to embedding energy-awareness in the design, in the devices and in the protocols of networks. It aims to reduce energy expenditures of telecommunication networks, and to minimize the GHG emissions, in order to achieve the sustainable development of human civilization. In recent years, the world's telecommunications journals and conferences are filled with new efforts in green networking research. To make network more energy efficiently, the academics have discovered different mechanisms so as to embed energy awareness and efficient into network terminal, interface, devices, infrastructure, and protocols.

Generally speaking, there are four main categories of energy efficient solutions: Adaptive Link Rate, Interface Proxying, Energy Aware infrastructure, and Applications. The Figure 2.1 below shows the four main technologies reported in the current literatures [3], [22]:

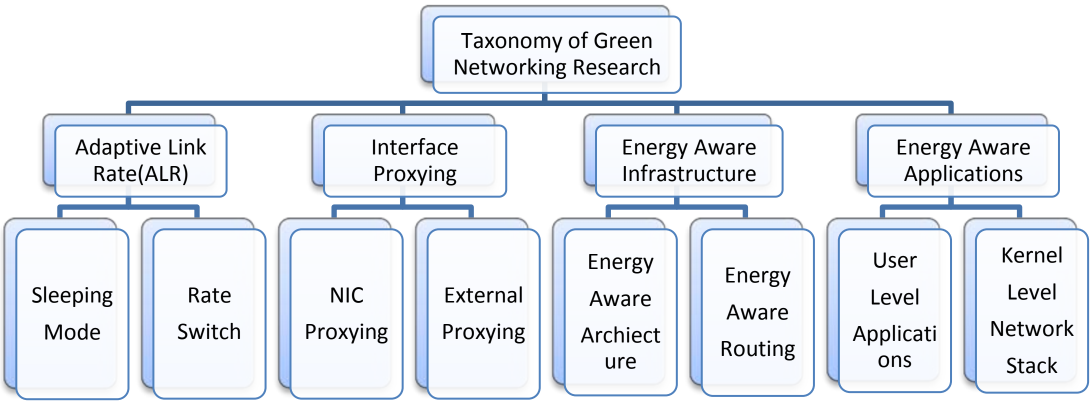


Figure 2.1 Classification of green networking technologies

2.1.1 Adaptive Link Rate

Empirical measurement has showed that energy consumption on an Ethernet link is largely independent of its utilization [4], [29-30]. In practice, even during the idle intervals where no frame is transmitted, the links are used to continuously send meaningless traffic in order to preserve synchronization and avoid the time required to send a long frame preamble. Therefore, the energy consumption of a link largely depends on its factory setting rather than the actual link load. The adaptive link rate [31], which follows the proportional computing paradigm, is designed to reduce energy consumption in response to low utilization in an on-line manner.

Generally, there are two mechanisms to apply adaptive link rate strategies. The first one is switching links into a low energy consuming status during (possibly short) idle periods, which are usually referred to as sleeping mode. The second one is reducing the line rate during low utilization period, which is known as rate switching. For example, since 100Mbit/s link consumes less energy than 1Gbit/s link, thus reducing 1Gbit/s link to 100Mbit/s at the off-peak time can reduce unnecessary energy waste. Some works such as [32-33], have compared the sleeping mode with rate switch strategies when they are both applied to processors and servers. They have reached the similar conclusion that sleeping mode strategy is better than its rival, due to a lower management complexity for a comparable performance level. The lower complexity comes with simpler optimization goals, which are minimizing idle energy and transition time, instead of complex load-proportional operation from each system component.

2.1.2 Interface Proxying

Interface Proxying [34], which delegates network-related traffic processing from power-hungry main board CPUs to low-power devices on-board of Network Interface Cards (NIC) or to external proxy devices. The NIC proxying implements a filtering or light processing of the received packets: the NIC may drop the chatter and handle the traffic requiring minimal computation, while the full system will be woken up only when non-trivial packets needing further processing are received. This allows energy saving through powering down the end systems, without disrupting their network connectivity. According to [26], this solution may apply to more than 90% of the received packets on a PC during idle periods. In addition, they propose longer sleeping intervals and a reduced number of system wake-ups for higher energy saving.

In addition, the offloading traffic filtering and processing to an external machine may have several advantages in the case of a larger LAN. Besides the economy of scale, as the proxy acts for a number of end-devices, it can feature a more efficient CPU and thus the offload the end-host from an even higher number of network-maintenance tasks. External energy aware proxies have also been evaluated in the context of Peer-to Peer (P2P) file-sharing applications [35-36]. In P2P, the edge device network presence represents a key issue to guarantee the robustness of the network: in this case, interface proxying represents a good way to save energy, without perturbing the system. This idea is explored in [35], with a prototype implementation for the Gnutella network in [36].

2.1.3 Energy Aware Infrastructure

In this category, the researchers have introduced energy-awareness feature into the network design such as architecture and the routing scheme.

(a) Energy aware architecture

There are two opposite proposals to build an energy-aware architecture: one is an incremental approach, which suggests building over existing infrastructures. For example, in [37] they have improved the Grid5000, which is a gird platform used by researchers. The study in [25] proposes to add the automatic adaptation of the link rate into the existing backbone network. The other solution is a clean-state approach, which advocates redesigning a brand new architecture, such as the studies in [38-39] claim that get rid of the existing optical networks which apply circuit switching, and redesign of new optical networks to suit the optical switching, because the optical switching is much more energy efficient, while offering an extremely large capacity.

(b) Energy aware routing

The energy aware routing [40], generally aims at aggregating traffic flows over a subset of the network devices and links, allowing other links and interconnection devices to be switched off by rerouting mechanism. This resource-consolidation approach could be a promising way to reduce the energy expenditure, especially in the off-peak period. The energy aware routing solutions should preserve connectivity and QoS, for instance by limiting the maximum utilization over any link, or ensuring a minimum level of path diversity [41]. The flow aggregation can be achieved, for example, through a proper configuration of the routing weights.

2.1.4 Energy Aware Applications

In the last category, energy reduction can be achieved by modifying the existing operating systems and applications, either on user-level or kernel-level.

(a) User-level applications

The typical application is Green Bit Torrent [42]. Peers openly advertise their energy-state, and green peers tend to avoid waking up idle peers, preferring to download the chunks from active ones. A probing mechanism is defined to test peers whose status is unknown such as the ones advertised by the tracker. In addition, the study in [43] redesigns the Telnet protocol in a green perspective, allowing the client to go to sleep after a given time and recover later. This requires a modification of the protocol implementation (e.g., the notification of the clients idle states to the server requires additional signalling), so as to avoid losing data without sending keep-alive messages.

(b) Kernel-level network stack

Other than greening the application-layer in the user-space, it is also possible to improve the transport-layer at kernel level for more energy-efficiency. The benefit of this approach is that these optimizations are then shared by all applications. More specifically, the modification of current TCP protocol in the operating systems kernels, would allow applications to open “greener” sockets, providing a framework for software developers. The study in [27] suggests one such modification, introducing explicit signalling at the transport layer via a specific option (TCP SLEEP) in the TCP header, in which case the other party will buffer data received from the application instead of sending it right away.

2.1.5 Summary

In summary, these four kinds of green technologies could reduce the energy expenditures from different perspective. The first two categories are quite mature, while the last two are expected more exploration. In this thesis, to achieve energy reduction, we apply energy aware routing, sleeping mode, and energy consumption rating strategy inspired by rate switching, into our energy aware survivable routing models.

2.2 Energy Efficient Approaches

In this section, the three energy efficient strategies which inspire us to propose and develop our new three energy aware routing algorithms are described in depth below. They are energy aware routing, sleeping mode, and also energy consumption rating strategies.

2.2.1 Energy Aware Routing

The energy aware routing approach has been first evoked in the position paper [1], which aims at aggregating traffic flows over a subset of the network devices and links, allowing other links and interconnection devices to be switched off or in sleep status [44]. The main idea can be briefly illustrated as the Fig.2.2 below. The three traffic flows highlighted in black can be aggregated into one working path coloured in red, which is shown in the right hand side of Fig.2.2, therefore those network elements (i.e., links and nodes) are not used can be turned into sleep state or shut down.

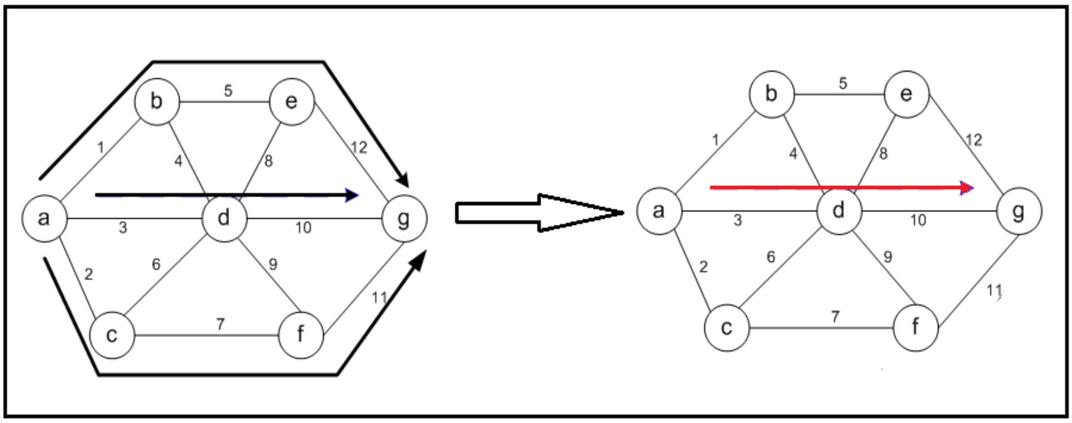


Figure 2.2 An illustration of energy aware routing approach

The energy aware routing could be a promising solution [45] to address the problem of energy waste in NGNs. It can be used to more efficiently route the traffic demands and switch off the unused network nodes and links to save the unnecessary energy consumption [46-47]. Recently, the potential energy saving capacity of energy aware routing is analysed by some studies, for example, in the work of [48] proposed an energy profile aware routing algorithm, which is assuming the network nodes capable of adapting their performance according to the actual traffic load. By applying it, a reduction in energy consumption of over 35% can be achieved. The study in [49] introduces a novel energy aware routing protocol (EARP) that is based on the autonomic network routing protocol. In this study, energy metrics, QoS metrics and the number of hops are considered. The result shows that the EARP achieves overall reduction of power consumption on average throughout the network. However, most of the recently studies have not taken the network survivability into consideration. For guarantying the network performance, [18], [50-51] just set a parameter between 0 and 1 to limit the maximum of link utilization. It clearly cannot avoid the packet loss if the working path (as shown in red colour in Figure 2.2) fails.

In summary, the energy aware routing could be a promising approach to reduce the energy usage of NGNs. However, the existing solutions of energy aware routing normally sacrifice the network robustness in order to achieve the maximum energy reduction [52]. Therefore, our objective is to use energy aware routing to achieve energy reduction but also maintain the same level of network survivability performance.

2.2.2 Sleeping Mode

The sleeping mode is a subclass of adaptive link rate strategies, which often refers to the network devices or part of them can turn themselves entering very low energy states, while all their functionalities are frozen. Thus, the sleeping/standby states can be considered as deeper idle states, characterized by higher energy saving and much larger wake-up times.

The sleeping mode is a state of the art technology, which is still not widely applied into the existing networks. Because today's networking devices are commonly designed to be fully available all the time, due to telecom companies put more priority on service resiliency rather than energy saving. Therefore, there is a basic problem needs to be addressed: when a device goes sleeping, how to maintain its network connectivity? For addressing this problem, [31] propose to add a "proxy", namely Network Connectivity Proxy (NCP), between the sleeping device and network. This NCP will process the low-level network presence tasks during the idle time. The NCP and the sleeping device can exchange two kinds of messages: one is application-specific, which register sleeping host's applications and services to the NCP. These messages contain the description of application connections, and of application "routine" messages. The other message is wakeup/sleep signals, which trigger the NCP when the host goes to sleep, or to wake-up the host when the NCP receives a traffic demand request. Some other works such as [53] use a shadow port to handle the synchronizing signal on behalf of a cluster of sleeping ports, also use a buffer in the device's interface to store the packets received during the sleeping intervals, and then process them when it wakes up.

In this thesis, how to implement the sleeping mode in hardware is out of our scope. Here we hypnosis that the hardware is supporting sleeping mode. Moreover, we assume the sleeping mode in our new routing algorithms is similar to the literature [54], where the network components can be reactivated within a short time in case of a failure occurs.

2.2.3 Energy Consumption Rating Strategy

The studies in [4], [29-30] have showed that energy consumption on the current network device is largely independent of its utilization. In practice, even during the off-peak period, devices are still working on their full power no matter how lower the actual load is. Therefore, the energy consumption of a device largely depends on its configuration rather than the actual device's load.

For saving the wasted energy at the low utilization period, some works in [55-56], advocate using transmission rate switching approach. They define several transmission rates, from 10Mbit/s to 10Gbit/s. There is a non-negligible difference in the interface energy consumption, across the different data rates. When a device is at certain load, the interface will automatically choose a suitable rate to achieve energy saving. Other work such as [50] proposed a fully proportional model for network elements, which the energy consumption is exactly proportional linearly according to ratio of actual load/capacity usage. This model represents an ideal case where energy consumption varies linearly with the device utilization, ranging between 0 and full power. However, in the real world, it is difficult to implement this design requirement with current hardware technology.

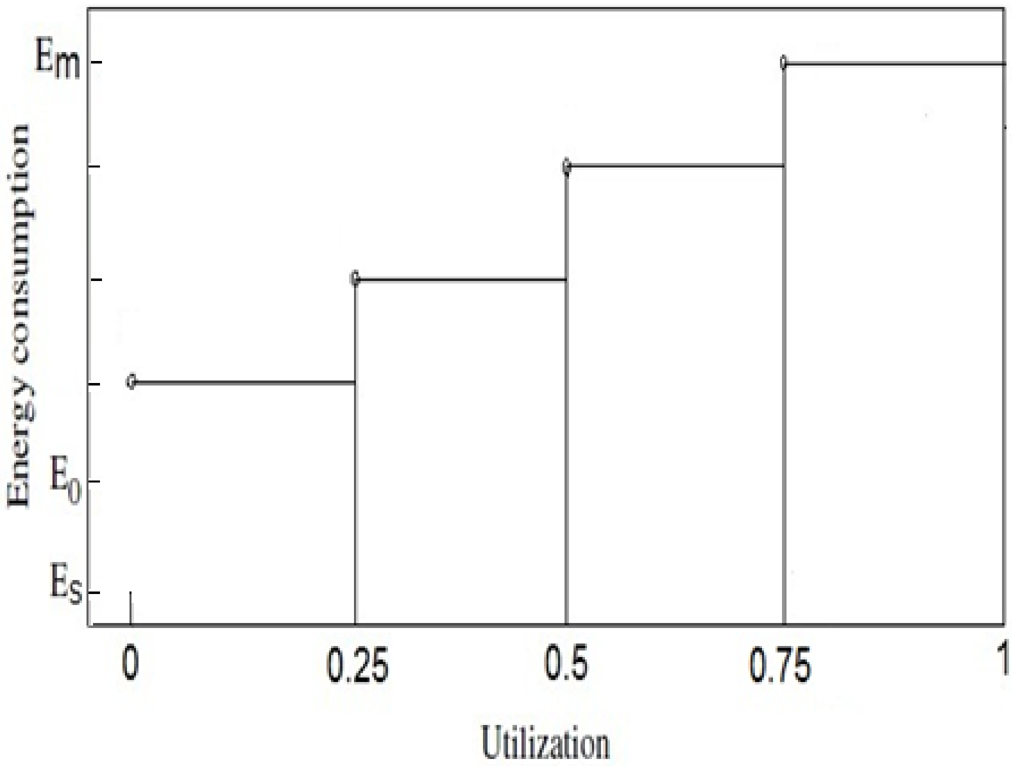


Figure 2.3 The six energy consumption levels of network devices

In our work, the energy consumption rating strategy is inspired by rate switching. We propose that the energy consumption of network components such as nodes and links are basically based on the actual traffic load passing them, which is similar to the assumption in [57]. The Fig.2.3 illustrates the six energy consuming rates in our scheme. For any network element a (a node or a link), the minimum value of energy expenditure E_0 , which represents its turning on status, and the maximum value E_m, which represents its maximized energy consumption. In addition, the value of E_{sa} represents the energy consumption when a network element in sleeping state. The energy consumption E_a can be configured as the following six levels:

(i) E_a = 0, represents the energy consumption as the device is switched off;

(ii) E_a = E_{sa}, represents the energy consumption as the device is set to a sleeping state;

(iii) E_a $= 25\%(E_{ma} - E_{0a})$ + E_{0a}, represents the energy consumption as its traffic load is less than or equal to 25% of its capacity;

(iv) $E_a = 50\%(E_{ma} - E_{0a}) + E_{0a}$, represents the energy consumption as its traffic load is greater than 25%, but less than or equal to 50% of its capacity;

(v) $E_a = 75\%(E_{ma} - E_{0a}) + E_{0a}$, represents the energy consumption as its traffic load is greater than 50%, but less than or equal to 75% of its capacity;

(vi) $E_a = E_{ma}$, represents the energy consumption as its traffic load is greater than 75% of its capacity, and operates at its full power.

2.3 Network Survivability Approaches

Network survivability [28] is the ability of the network to provide and maintain an acceptable level of service in the case of various failures to the normal operation. It reflects the ability of a network to continue to function during and after failures. Nowadays, the network failures are frequent [58], such as fibre cuts, key components malfunction, or router hardware/software failures. When an element of the network fails, all the traffic passing through this element is lost (i.e., at least during the recovery procedure), which can really decrease the QoS perceived by all the users of the network. Especial for the green networking approaches, in which the traffics flows tend to be aggregated to several high capacity links. If one of these active links fails may lead to a more significant data loss. For this reason, there is a critical need to apply protection scheme that will allow the network to quickly recover from any failure it may encounter. In on-line traffic engineering, the network must be able to compute and establish a path from an ingress router to an egress one and to protect it against failures, based on the requested bandwidth and QoS requirements of the traffic low. In general, there are three kind of backup protection mechanisms such as 1+1 backup protection scheme, 1:1 backup protection scheme, and shared backup protection scheme.

2.3.1 1+1 Backup Protection

In the 1+1 backup protection scheme [59], for each traffic flow, it needs to compute two completely disjoint paths from the ingress to the egress nodes, one is the primary path, and the other is the backup path. Both paths are used simultaneously: all packets are duplicated at the ingress nodes and sent on both paths to the egress nodes. The egress node continuously monitors both inputs and selects the ‘‘best’’ one to receive and process [60-61].

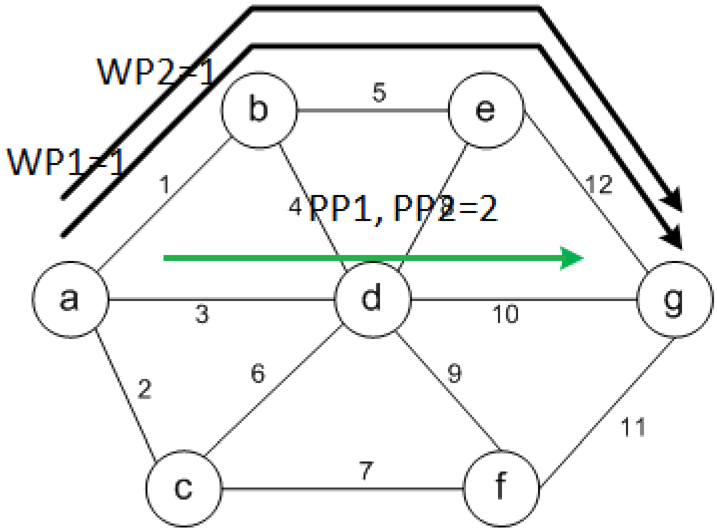


Figure 2.4 An illustration of 1+1 backup protection scheme

The Fig.2.4 illustrates 1+1 backup protection scheme. WP1 and WP2 are working paths for two traffic flows which are from node a to node g, each with the traffic volume of 1 unit. PP1 and PP2 are the protection paths corresponding to WP1 and WP2 respectively. The egress node g may choose receive WP1 or PP1, and WP2 or PP2, depends on the received signal quality.

This approach of protection has the advantage of fast receiver-driven recovery upon failure but is of course very costly in terms of bandwidth and energy consumption. Because 1+1 backup is the dedicated scheme, therefore no backup capacity can be shared. Moreover, both primary and backup path are working at the same time, the sleeping mode cannot be applied into the backup path so as to reduce energy expenditure.

2.3.2 1:1 Backup Protection

In the 1:1 scheme, only the primary path is used to forward packets while the backup path can be configured in sleeping mode. If a failure occurs in the primary path, a message is sent to the ingress node which swaps the traffic to the backup path from the primary path. Obviously the 1:1 protection induces more delay than the 1+1 scheme.

The failure has to be detected, and a message must propagate to the ingress node to trigger the recover actions.

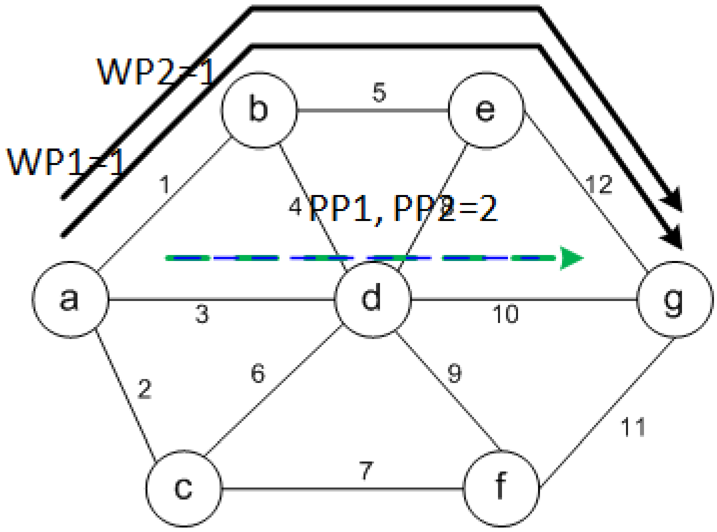


Figure 2.5 An illustration of 1:1 backup protection scheme

The 1:1 backup protection scheme is shown in Fig.2.5. Different from 1+1 backup protection, for the two traffic demands, the egress node g receives data from the primary paths WP1 and WP2. If failure happens on the primary path a – b – e – g (WP1 and WP2), the working path will swap to a – d – g (PP1 and PP2).

The advantage of the 1:1 solution is that a significant energy saving can be realized [62-63]. Indeed if we assume that only a single failure may happen in the network at any given time, not all backup paths can be activated simultaneously. The reserved network resources for independent backup paths can thus be switched into sleeping mode [64]. For example, PP1 and PP2 could be turn into sleep state in Fig.2.5.

2.3.3 Shared Backup Protection

In the shared backup scheme [65], only when the two traffic flows' primary paths are completely disjointed, the bandwidth can be shared in the overlapped backup links. The reserved capacity will be the lager one of the two, rather than the total amount of the two.

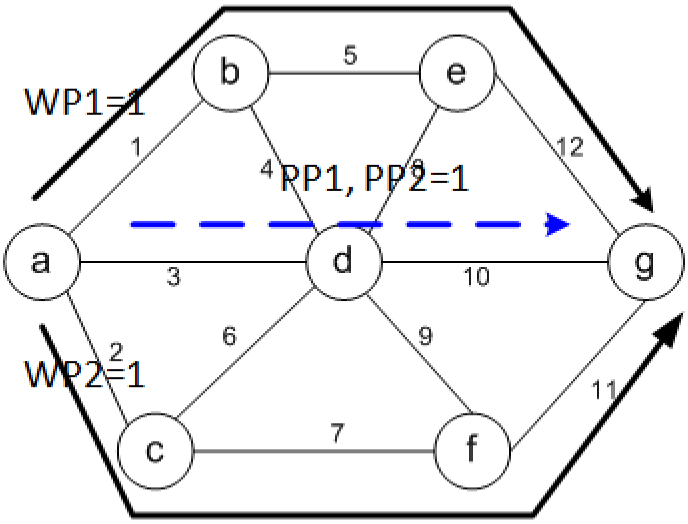


Figure 2.6 An illustration of shared backup protection scheme

The Fig.2.6 illustrates the shared backup protection scheme. Because the two traffics' primary paths WP1 and WP2 are disjointed, and their backup path PP1 and PP2 are overlapped, therefore the two traffics can share the backup bandwidth on backup path a – d – g. If WP1 or WP2 fails, the working path can switch to the backup path. In our thesis, we assume there is only one failure happened at a time. In other word, WP1 and WP2 would not fail at same time.

The shared backup protection mechanism can effectively reduce the capacity consumption, however it may consume more energy than the other two, because to separate two traffic flows' primary path in disjointness may need more working nodes and links. The backup links can be switched into sleeping mode in order to save energy expenditure.

2.3.4 Comparison of Different Protection Mechanisms

The Fig.2.7 below illustrates the difference among the 1+1 backup scheme, 1:1 backup scheme, and the shared backup scheme in (a), (b), (c) respectively. We assume there are two working traffic flows i.e., WP1, WP2 are the primary path of them and each has 1 unit of capacity requirement. The PP1 and PP2 are represents the protection paths for WP1 and WP2 respectively.

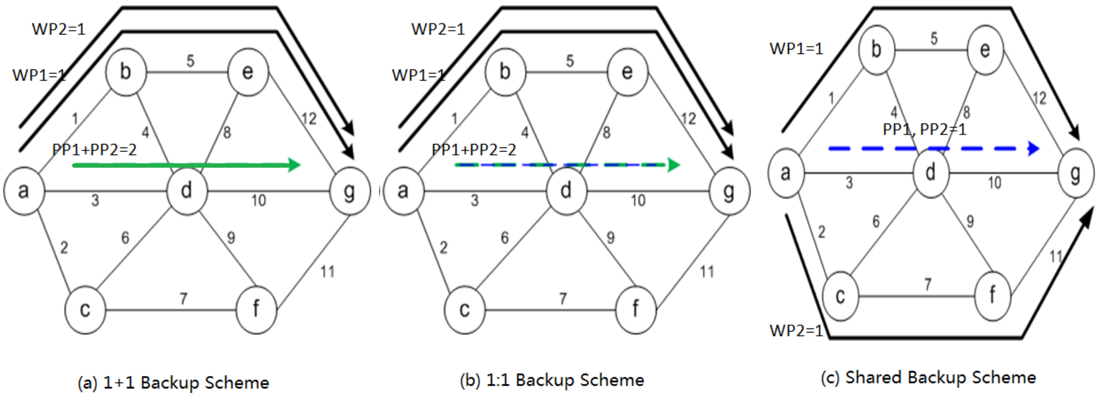


Figure 2.7 Comparison of the three backup protection schemes

The diagram (a) shows how the 1+1 backup scheme works, the backup paths PP1 and PP2 are working with the primary path WP1 and WP2. Therefore the network needs to turn on 5 nodes and 5 links, with the total capacity of 10 units to meet the traffic demand.

For 1:1 backup scheme (b), the backup resources can be switched into sleeping mode. From the aspect of energy consumption, there are 4 nodes and 3 links is in working mode, 1 node and 2 links is in sleeping mode. For the capacity usage aspect, the system still needs to reserve 10 units of bandwidth in total for the two traffic flows.

While the Figure 2.7 (c) shows the solution of the shared backup scheme. To meet the requirements of backup sharing, the two primary paths of WP1 and WP2 have to be disjointed completely. In this scheme, the network turns 6 nodes and 6 links in working mode, and 1 node and 2 links in sleeping mode. However, from the capacity point of view, it just needs 8 unit of capacity in total.

The table 2.1 below compares the three protection mechanisms in detail, both from energy consumption and bandwidth reservation aspects. From the table, it can be seen that the 1:1 backup scheme can be the best approach to save energy, while the shared backup can reserve the fewest bandwidth but need the most nodes and links in working mode.

Table 2.1 The energy and capacity demands of the three protection schemes

	Energy Consumption		Bandwidth Reservation
	Working	Sleeping	
1+1 backup scheme	5 nodes 5 links	N/A	10 units
1:1 backup scheme	4 nodes 3 links	1 node 2 links	10 units
shared backup scheme	6 nodes 6 links	1 node 2 links	8 units

2.4 Summary

In this chapter, we firstly review the state of art of green networking technologies. Then we have discussed the approaches applied into our new routing algorithms for energy reduction and network survivability aspect respectively. On one hand, for energy saving aspect, the energy aware routing approach is introduced firstly. Secondly, an in-depth description of sleeping mode is provided. At last, the energy consumption rating strategy is described, following that with our proposed six-level of energy consumption pattern. On the other hand, for network survivability aspect, we give a background introduction on 1+1 backup protection scheme, 1:1 backup protection scheme, and also shared backup protection scheme. Then the advantages and disadvantages of these three schemes have been compared and discussed. Based on the above four mechanisms, we propose and develop our new three routing algorithms to tackle the trade-off problem between energy reduction and network survivability.

Chapter 3

Energy Aware Survivable Routing Algorithms

The problems of trade-off between energy efficiency and network survivability can be modelled using Integer Linear Programming (ILP) formulations [66]. In this chapter, firstly, we introduce the background knowledge on ILP modelling, and then present the notations used in our models. Following that, we propose the formulations for our new three energy aware survivable routing models: Energy Aware 1+1 Backup Protection (EABP 1+1), Energy Aware 1:1 Backup Protection (EABP 1:1) and Energy Aware Shared Backup Protection (EASBP).

3.1 Introduction on ILP Modelling

The integer linear programming plays an important role in algorithm design. Lot of combinatorial optimization problems can be formulated as integer linear programming problems. But it is NP-Complete [67]. One potential solution to solve the ILP problems in polynomial time using linear programming with the technique of LP relaxation[68]. Thus, linear programming and the concepts of rounding and duality are very useful tools in the design of approximation algorithms for many NP-Complete problems.

In integer linear programming, our aim is to find an assignment that maximizes or minimizes the objective while also satisfying all the constraints [69]. Typically, the constraints are given in the form of inequalities. For example, the standard forms of minimize integer linear programming instance looks like:

$$\text{Minimize} \quad c_1 x_1 + c_2 x_2 + \dots c_n x_n$$

Subject to

$$\begin{aligned}
&a_{11} x_1 + a_{12} x_2 + \dots a_{1n} x_n \geq b_1 \\
&a_{21} x_1 + a_{22} x_2 + \dots a_{2n} x_n \geq b_2 \\
&\quad \dots.. \\
&a_{m1} x_1 + a_{m2} x_2 + \dots a_{mn} x_n \geq b_m \\
&\quad \forall i, x_i \geq 0
\end{aligned}$$

Any assignment of values for variables x_i which can satisfy the constraints is called a feasible solution. The challenge in integer linear programming is to find a feasible solution that can also maximizes or minimizes the objective function.

In our work, we tackle the trade-off optimization problem between network energy efficiency and network survivability by using energy aware survivable routing approaches. This sort of trade-off problem falls in the category of capacitated multi-commodity minimum cost flow problems (CMCF). In other words, the problem in which multiple commodities have to be routed over a graph with constraints [70]. Generally speaking, this problem is also categorized as combinatorial optimization, which can be precisely modelled using ILP formulation [4], [16]. ILP can be used for determining a way to achieve the best outcome (such as maximum profit or lowest cost) in a given mathematical model for a list of requirements and constraints represented as linear relationships [71]. In this research, we have proposed the ILP models to tackle our optimization problems.

3.2 Notation

The notation used for the ILP formulations in this thesis is defined by the following indexing rules:

- *(s, d)* which represents the node pair of the source and destination nodes for a connection request;
- *(x, y)* and *(m, n)* are the node pairs representing the links in the network topology traversed by primary and backup routes respectively.

In order to describe the mathematical model and problem formulation, the following notations are further introduced for parameters and variables.

Given parameters:

• G (N, L): A network topology consisting of a set of N nodes and a set of L links.

• a : Network element, either be a node or a link. For example, a is i which means that a represents node i; if a is ij, it means that a represents the link between node i and node j.

• l_a: The total traffic load of primary path of a. I.e. l_i and l_{ij} stand for the total amount of capacity usage of node i and link ij for providing primary paths.

• $l_a^{'}$: The total traffic load of backup path of a. I.e. l_i and l_{ij} stand for the total amount of capacity usage of node i and link ij for providing backup paths.

• C_a: The capacity of a, which indicates the maximum capacity of it.

• α: An arbitrary value to preserve QoS, which is a configurable utilization threshold of network elements. Nowadays, the network operators adopt as common practice to limit the load of the links to enforce QoS and robustness in their networks, α is between 0 and 1.

• E_{ma}: The maximum energy consumption of network element a when it is turn on. It indicates the full power of a network element.

• E_{0a}: The minimum energy consumption of network element a when it is turn on. It indicates the minimum power to maintain a network element in working status.

• E_{sa}: The energy consumption of network element a when it is in sleeping mode. It represents the sleeping status' power consumption of a network element.

• M: Constant value used in the big-M constraints. M is a "big" number (i.e., greater than twice the maximum nodes capacities).

• T_i: The request traffics matrix. i is the index of the matrix. I.e. T_1 is the first line of the traffic demands, and it could be from node i to node j with the volume of x Gbit.

Variables:

• p_{xy}^{sd}: Number of path requests from s to d which passes through link *(x, y)* in their primary path.

• ∂_{mn}^{sd}: Number of path requests from s to d which passes through link *(m, n)* in their backup path.

• k_a: A binary variable. If k_a = 1, network element a is in working status.

• s_a: A binary variable. It indicates whether a network element in sleeping mode or not. If s_a = 1, network element a is in sleeping state for backup protection. If s_a = 0, network element a is either in primary path or has no load at all.

• $z1_a$: A binary variable. If $z1_a$ = 1, network element a adapts to the first working level of energy expenditure.

• $z2_a$: A binary variable. If $z2_a$ = 1, network element a adapts to the second working level of energy expenditure.

• $z3_a$: A binary variable. If $z3_a$ = 1, network element a adapts to the third working level of energy expenditure.

• $z4_a$: A binary variable. If $z4_a$ = 1, network element a adapts to its maximum power.

• E_a: The total energy consumption of network element a.

• k_{L,T_i}: A binary variable. If k_{L,T_i} = 1, link L is used as a primary link by a connection request T_i. If k_{L,T_i} = 0, link L is not used as a primary link by a connection request T_i.

• $k1_{L,T_i}$: A binary variable. If $k1_{L,T_i}$ = 1, link L is used as a backup link by a connection request T_i. If $k1_{L,T_i}$ = 0, link L is not used as a backup link by a connection request T_i.

• $p0_{T_1,T_2}$: A binary variable. If $p0_{T_1,T_2}$ = 1, the primary paths of T_1 and T_2 have overlapped link, which means T_1 , T_2cannot share backup. If $p0_{T_1,T_2}$ = 0, the primary paths of T_1 and T_2 are disjointed, which means T_1 , T_2 may share backup capacity.

• $p1_{L,T_1,T_2}$: A binary variable. If $p1_{L,T_1,T_2}$ = 1, the link L used as backup paths for both T_1 and T_2, which means T_1 , T_2 may share backup in L. On the other hand, if $p1_{L,T_1,T_2}$ = 0, the link L used as backup paths for either T_1 or T_2, and also may not be used as backup for T_1 and T_2. In this case, T_1 and T_2 cannot share backup resource in L.

• $p2_{L,T_1,T_2}$: A binary variable. If $p2_{L,T_1,T_2}$ = 1, T_1 and T_2 can share backup in link L. If $p2_{L,T_1,T_2}$ = 0, T_1 and T_2 cannot share backup in link L.

• C_{L,T_1,T_2}: The amount of backup capacity can be shared by T_1 and T_2 in link L. In other words, this amount can be saved.

3.3 Energy Aware 1+1 Backup Protection (EABP 1+1)

Firstly, we propose the 1+1 backup protection scheme is embedded in EABP 1+1, so that the backup path will transmit the duplicated information simultaneously as the primary path. Base on this protection scheme, the nodes and links on the backup path cannot be switched into sleeping mode. Our goal is to minimize the whole network's overall energy consumption, which includes the energy consumption of nodes and links. Therefore EABP 1+1 will aggregate traffic flows to a small subset of network, then turn off those unloaded network elements to achieve energy saving. The ILP formulations of EABP 1+1 are listed as follow:

Objective

Minimize

$$\sum_{n \in N} E_n + \sum_{(x,y) \in L} E_{xy} \qquad (1)$$

The objective function (1) is to minimize the total energy consumption of active nodes and links in the network.

Constraints

$$\sum_{x \in N} p_{xk}^{sd} + \sum_{y \in N} p_{ky}^{sd} = \begin{cases} \gamma_{sd}, & k = d \\ -\gamma_{sd}, & k = s, \quad \forall k, s, d \in N \\ 0, & k \neq s, d \end{cases} \qquad (2)$$

$$\sum_{m \in N} \partial_{mk}^{sd} + \sum_{n \in N} \partial_{kn}^{sd} = \begin{cases} \gamma_{sd}, & k = d \\ -\gamma_{sd}, & k = s, \quad \forall k, s, d \in N \\ 0, & k \neq s, d \end{cases} \qquad (3)$$

Constraints (2) and (3) are flow conservation constraints for routing γ_{sd}number of connection requests from node *s* to *d* for primary and backup paths respectively. For a traffic request T_i, if *k* is a destination node, there are a volume of T_i inflow to it; if *k* is a source node, there are the volume of T_i outflow from it; if k is an intermediate node, the total inflows should be equal to the outflows.

$$\partial_{mn}^{sd} = 0 \ \forall (s,d) \in N \quad \forall (m = x, n = y) \in L \qquad (4)$$

Constraint (4) guarantees link disjointness of a failure in primary from the backup path which assures that if a link *(x, y)* fails, the connection from s to d cannot be routed through link *(x, y)*.

$$\sum_{s,d \in N} p_{xy}^{sd} = l_{xy} , \forall (x,y) \in L \qquad (5)$$

$$\sum_{s,d \in N} \partial_{mn}^{sd} = l_{mn}^{'}, \forall (m,n) \in L \qquad (6)$$

l_{xy} is the total traffic load of link *(x, y)* using by primary paths. l'_{mn} is the total traffic load of link *(m, n)* using as backup paths. Therefore, traffic load of primary paths on link *(x, y)* is defined in constraint (5). Traffic load of backup paths on link *(m, n)* is defined in constraint (6).

$$\sum_{(i,n) \in L} l_{in} + \sum_{(n,i) \in L} l_{ni} = l_n, \quad \forall\, n \in N \qquad (7)$$

$$\sum_{(i,n) \in L} l_{in}^{'} + \sum_{(n,i) \in L} l_{ni}^{'} = l_n^{'}, \quad \forall\, n \in N \qquad (8)$$

We assume node load to be directly sum of the traffic entering and leaving the node, therefore constraints (7) and (8) define traffic load of primary paths and backup paths converge to node n respectively.

$$\alpha C_{xy} \geq l_{xy} + l_{xy}^{'}, \ \forall (x,y) \in L \qquad (9)$$

$$\alpha C_n \geq l_n + l_n^{'}, \ \forall n \in N \qquad (10)$$

Constraints (9) and (10) are to preserve QoS, no links or nodes should reach 100% utilization or more in general, an arbitrary value that the network operator considers safe enough. C_{xy} and C_n are the capacity of link and node respectively. The α is in the range of 0 to 1. In our thesis, it has been set as 0.8.

$$\mathrm{M}k_{xy} \geq l_{xy} + l_{xy}^{'}, \ \forall (x,y) \in L \qquad (11)$$

$$\mathrm{M}k_n \geq l_n + l_n^{'}, \ \forall n \in N \qquad (12)$$

The constraints (11) and (12) define the value of decision variables according to whether a link or a node is used or not. k_a is a binary variable. Its value will be 1 when a is used in working status, otherwise it equals to 0. M is a “big” number (i.e. greater than twice the maximum nodes’ capacities) used to force the variable k_a to take the value 1 when a has a load greater than 0, and the value 0 when l_a = 0.

$$k_n \geq z1_n + z2_n + z3_n + z4_n, \ \forall n \in N \qquad (13)$$

$$(l_n + l_n^{'})/C_n \geq 25\% z1_n + 50\% z2_n + 75\% z3_n + z4_n, \quad \forall n \in N \qquad (14)$$

$$E_n = (25\% z1_n + 50\% z2_n + 75\% z3_n + z4_n)(E_{mn} - E_{0n}) + k_n E_{0n}, \quad \forall n \in N \qquad (15)$$

In the previous chapter, we have introduced the six levels of energy consumption for network elements. The first level is when network element a has no load, the energy consumption is none. The second level is when network element a is in sleeping mode, its energy usage is E_{sa}. The remaining four levels represent a is in working status according to its load. If a network element's load less than or equal to 25% of its capacity, a is working on the first working level controlled by $z1_a$. If its load greater than 25%, but less than or equal to 50% of its capacity, the network device a is working on the second working level controlled by $z2_a$. Similarly, $z3_a$ and $z4_a$ decide the network element a working on the third or the forth working level.

The combination of constraints (13), (14), and equation (15) ensures each node can be assigned to the proper energy consumption level according to their load. Constraint (13) let node n can be only working on one of the four working levels. Because k_n is binary, thus $z1_n$, $z2_n$, $z3_n$, and $z4_n$ are no more than one of them can be set to value 1.The constraint (14) means the working level of node n will be decided by the actual load. We can see the ratio of load divided by node's capacity is in the range of 0 to 1. If the ratio is no more than 1/4, the node is working on level 1; if the ratio is from 0.25 to 0.5, the node is working on level 2; if the ratio is no more than 0.75, node working on level 3; if the ratio is larger than 0.75, node working on full power. The equation (15) calculates the energy consumption of node n, E_{0n} is the minimum energy consumption of node n when it is turn on.

$$k_{xy} \geq z1_{xy} + z2_{xy} + z3_{xy} + z4_{xy}, \ \forall (x,y) \in L \quad (16)$$

$$(l_{xy} + l'_{xy})/C_{xy} \geq 25\% z1_{xy} + 50\% z2_{xy} + 75\% z3_{xy} + z4_{xy}, \ \forall (x,y) \in L \quad (17)$$

$$E_{xy} = (25\% z1_{xy} + 50\% z2_{xy} + 75\% z3_{xy} + z4_{xy})(E_{mxy} - E_{0xy}) + k_{xy} E_{0xy}, \quad \forall (x,y) \in L \quad (18)$$

Similarly, the constraints (16), (17), and equation (18) are for links' energy consumption rate assignment constrains, which ensure each link is allocated to the proper energy consumption level according to their workload. In addition, the energy consumption of link *(x, y)* is calculated by equation (18).

3.4 Energy Aware 1:1 Backup Protection (EABP 1:1)

Secondly we propose the EABP 1:1 model which integrated the 1:1 backup protection scheme. The backup path will be only active when a node or link failure occurs in the primary path. Therefore, the sleeping mode could be introduced into the network components in backup path. Our goal is to minimize the energy expenditure of the whole network. Basically, we develop EABP 1:1 by introducing sleeping mode into EABP 1+1. Since sleeping mode or turn-off status consumes significantly less energy than working status, the EABP 1:1 model tends to aggregate traffic flows to existing working devices, then switch off unloaded elements and turn backup resources into sleeping mode as many as possible. Therefore, the EABP 1:1 model is highly expected to consume less energy than EABP 1+1. The ILP formulations of EABP 1:1 are as follows:

Objective:

Minimize

$$\sum_{n \in N} E_n + \sum_{(x,y) \in L} E_{xy} \qquad (19)$$

The objective (19) is to minimize energy consumption of nodes and links, which includes network element used by primary path and in sleeping state.

Constraints: (2)-(10),

Because EABP 1:1 is based on EABP 1+1, thus constrains (2) – (10) can be shared.

$$\mathrm{M}k_{xy} \geq l_{xy} \;, \quad \forall (x,y) \in L \qquad (20)$$

$$\mathrm{M}k_{n} \geq l_{n} \;, \quad \forall n \in N \qquad (21)$$

The constraints (20) and (21) define the value of decision variables according to whether a link or a node is used by any primary path. M has big value, therefore if l_a is greater than 0, k_a will be set as 1.

$$k_n + s_n \leq 1 \,, \quad \forall n \in N \qquad (22)$$

$$l'_n - M\, l_n \leq M\, s_n \,, \quad \forall n \in N \qquad (23)$$

The constraints (22) and (23) define that a node is used in primary path or switched into sleeping mode. s_a is a binary variable, which indicates whether a network element in sleeping mode or not. If s_a = 1, network element a is in sleeping state for backup protection. If s_a = 0, network element a is either in primary path or has no load at all. Constraint (22) restricts node n cannot be in both working status and sleeping status. Constraint (23) sets node n in sleeping mode only when this node is not used as primary by any connection request T_i .

$$k_{xy} \quad + \quad s_{xy} \quad \leq \quad 1 \ , \quad \forall (x,y) \in L \qquad (24)$$

$$l'_{xy} \ - \ M \, l_{xy} \leq \ M s_{xy} \ , \quad \forall (x,y) \in \ L \qquad (25)$$

Similarly, Constraints (24) and (25) define links used by primary path or switched into sleeping mode.

$$k_n \quad \geq \ z1_n \ + \ z2_n \ + \ z3_n \ + z4_n \, , \ \forall n \in N \qquad (26)$$

$$l_n \, / C_n \ \geq \ 25\% z1_n \ + \ 50\% z2_n + 75\% \, z3_n \ + \ z4_n \, , \quad \forall n \in N \qquad (27)$$

$$E_n \ = (\ 25\% z1_n + 50\% z2_n \ + \ 75\% \, z3_n + \ z4_n) \ (\ E_{mn} - \ E_{0n}) + k_n \ E_{0n} \ + s_n \ E_{sn} \, , \quad \forall n \in N \qquad (28)$$

The constraints (26), (27), and equation (28) ensure each node is allocated to the proper energy consumption level according to their load. Constraint (26) forces node n can be working on only one of the four working levels. It confines only one of $z1_n$, $z2_n$, $z3_n$, and $z4_n$ could be set to value 1. Constraint (27) means the working level of node n will be decided by the actual load, but it is different to the previous model. Here only the capacity of primary working path will be taken into calculate, because the backup resources are just reserved not actually transmitted as EABP 1+1. We can see the ratio of load divided by node's capacity is in the range of 0 to 1. If the ratio is less than or equal to 1/4, node is on first working level; if the ratio is large than 1/4, and less than or equal to 1/2, node is on working level 2; if the ratio is large than 1/2, and less than or equal to 3/4, node is on working level 3; if the ratio is above 3/4, node is working on full power. The equation (28) calculates the energy consumption of node n. Compares to the previous model, here we add a new term $s_n \ E_{sn}$, which means when node n is in sleeping mode, energy consumption of n will be equal to E_{sn}. E_{sn} is the energy consumption of node n when it is in sleeping mode.

$$k_{xy} \geq \ z1_{xy} + \ z2_{xy} + z3_{xy} \ + z4_{xy}, \qquad \forall (x,y) \in L \qquad (29)$$

$$l_{xy} \, / C_{xy} \ \geq 25\% z1_{xy} + 50\% z2_{xy} + 75\% \, z3_{xy} \ + z4_{xy} \, , \qquad \forall (x,y) \in L \qquad (30)$$

$$E_{xy} \ = (\ 25\% z1_{xy} + 50\% z2_{xy} \ + 75\% \, z3_{xy} + z4_{xy}) \ (\ E_{mxy} - E_{0xy}) + k_{xy} \ E_{0xy} \ + \ s_{xy} \, E_{sxy} \ , \quad \forall (x,y) \in L \qquad (31)$$

The power expenditure of links is confined by the constraints (29), (30), and equation (31). The three formulations ensure each link is allocated to the proper energy consumption level according to their load. The energy consumption of each link L will be calculated out by equation (31). The difference between EABP 1+1 model and

EABP 1:1 model is that the sleeping mode is introduced in the latter. Thus for switching off unnecessary network element and turning backup resources into sleeping mode, the routing strategy of EABP 1:1 may differ from EABP 1+1. However, the backup resources of EABP 1:1 should consume considerable less amount of energy compared with that of EABP 1+1.

3.5 Energy Aware Shared Backup Protection (EASBP)

In the third model, we have proposed the EASBP algorithm which applied the shared backup protection scheme. In this model, we are trying to make the capacity in the backup path can be shared as much as possible under a single failure scenario. The backup paths are reserved in case of the primary path break down, and the sleeping mode is used for the backup links. The goal of EASBP is to minimize the energy usage as well as making the backup bandwidth share to a large extend. Because two disjointed traffic flows may share backup path, thus EASBP cannot aggregate too much traffics into high capacity links and nodes. This model may not achieve as much energy reduction as EABP 1:1, but it could save capacity consumption compares with the other two. The ILP formulations of EASBP are as follows:

Objective:

Minimize

$$\left(\sum_{n\in N} E_n + \sum_{(x,y)\in L} E_{xy}\right) + \mathcal{E}\left(\sum_{(x,y)\in L} l_{xy} + \sum_{(x,y)\in L} l'_{xy}\right) \qquad (32)$$

The objective (32) here is to minimize the total energy consumption as well as capacity consumption, where $\mathcal{E}$ is a scale factor to make these two metric in the similar range.

Constraints: (2)-(5), (7)-(10), (20)-(31)

EASBP can share the common constraints (2)-(5),(7)-(10) from EABP 1+1. In addition, it has applied sleeping mode for backup resources, therefore it can share constraints (20)-(31) from EABP 1:1. The difficulties of developing EABP are how to separate those connection requests' primary paths to achieve backup sharing and how to calculate the sharable amount.

$$p0_{T_1,T_2} \geq k_{L,T_1} + k_{L,T_2} - 1, \qquad \forall\ T_1,\ T_2 \in\ T_i \qquad (33)$$

The constraint (33) checks whether the primary path of T_1 and T_2 is disjointed or not. Here k_{L,T_i} is a binary variable. If k_{L,T_i} = 1, link L is used as a primary link by a connection request T_i. If k_{L,T_i} = 0, link L is not used as a primary link by a connection request T_i. The variable $p0_{T_1,T_2}$ equals to 1 when the primary paths of T_1 and T_2 have overlapped link, which make T_1 and T_2 unable to share any backup capacity due to their primary paths not being disjointed. If $p0_{T_1,T_2}$ = 0, the primary paths of T_1 and T_2 are disjointed, so that they have the potential to share the backup capacity.

$$p1_{L,T_1,T_2} \geq k1_{L,T_1} + k1_{L,T_2} - 1, \quad \forall\ T_1,\ T_2 \in\ T_i \qquad (34)$$

Then the constraint (34) checks whether T_1 and T_2 have overlapped links or not on their backup path. These overlap links have the potential to be shared. $k1_{L,T_i}$ is a binary variable. If $k1_{L,T_i}$ = 1, link L is used as a backup link by a connection request T_i. If $k1_{L,T_i}$ = 0, link L is not used as a backup link by a connection request T_i. The variable $p1_{L,T_1,T_2}$ equals to 1 when the backup paths of T_1 and T_2 have overlapped in link L, in this case, T_1 and T_2 may share backup in link L.

$$p2_{L,T_1,T_2} \geq p1_{L,T_1} - p0_{T_1,T_2}\ , \quad \forall\ T_1,\ T_2 \in\ T_i \qquad (35)$$

The constraint (35) defines $p2_{L,T_1,T_2}$ which is an indicator to show whether the backup resources of T_1 and T_2 can be shared or not. Only when $p1_{L,T_1,T_2}$ = 1 and $p0_{T_1,T_2}$ = 0, then $p2_{L,T_1,T_2}$ equals to 1, which shows that T_1 and T_2 can share backup in link L. Otherwise, $p2_{L,T_1,T_2}$ = 0, means T_1 and T_2 cannot share backup bandwidth.

$$C_{L,T_1,T_2} = p2_{L,T_1,T_2} * \min(T_1,\ T_2)\ , \quad \forall\ T_1,\ T_2 \in\ T_i \qquad (36)$$

Equation (36) ensures that the possible sharable capacity C_{L,T_1,T_2} will be the small one of the two traffics T_1 and T_2. In other words, the capacity of the large one has been reserved in link L.

$$l'_{mn} = \sum_{s,d\in N} \partial_{mn}^{sd} - 0.5 * \sum_{T_1,T_2\in T} C_{L,T_1,T_2}\ , \qquad \forall (m,n) \in L,\ \forall\ T_1,\ T_2 \in\ T_i \qquad (37)$$

The total backup bandwidth on link (m, n) that needs to be reserved is defined in equation (37), which means the reserved backup capacity on link L equals to the total backup of all volumes of T_i minus the amount of shared capacity. Since T_1 and T_2 both belong to T_i , when we calculate the total shared part, it will be twice as it should be. Therefore the overall shared capacity need to multiply by 0.5.

3.6 Summary

In this chapter, we firstly introduced the Integer Linear Programming (ILP) modelling approach which can be used to model the trade-off optimization problems between energy consumption and network survivability. Using this approach, we have developed three energy aware routing models: Energy Aware 1+1 Backup Protection (EABP 1+1), Energy Aware 1:1 Backup Protection (EABP 1:1), Energy Aware Shared Backup Protection (EASBP). In each corresponding section, we have presented the ILP formulations for the three models respectively, and also explained them in depth.

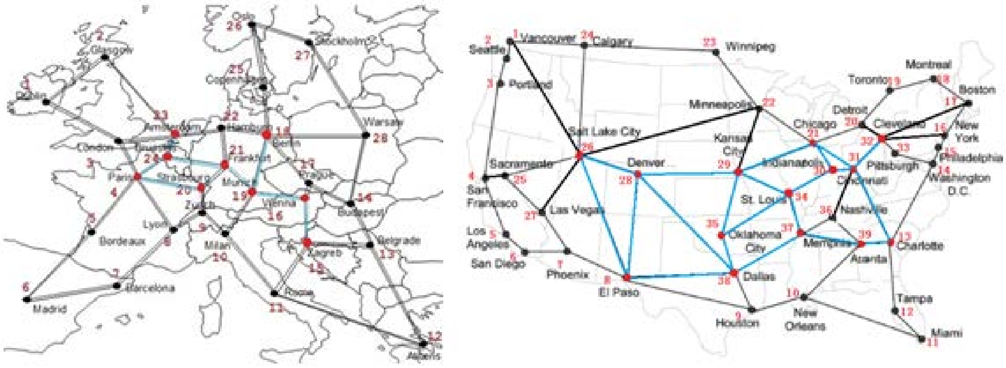
Chapter 4

Case Studies in CPLEX Optimization Studio

In order to validate and evaluate the performance of our proposed three models, we have conducted extensive case studies. The main goal is to show that, for a given static traffic demand, it is possible to turn off some network elements to advance the energy efficiency but still can guarantee the network survivability. We have used the Optimization Programming Language (OPL) [72] and IBM ILOG CPLEX Optimization Studio [73] to conduct these case studies. The network scenarios such as topologies, parameters of network elements and traffic data are presented. Following that, the two network performance metrics such as energy and capacity consumptions of Energy Aware 1+1 Backup Protection (EABP 1+1), Energy Aware 1:1 Backup Protection (EABP 1:1) and Energy Aware Shared Backup Protection (EASBP) are studied and analysed with the illustrative numerical results.

4.1 Experimental Topology and Network Configuration

The case studies are carried out upon two referenced topologies from the SNDlib [74], which is a library of test instances for Survivable fixed telecommunication Network Design. The two network topologies are depicted as Fig.4.1 (a) and (b). The first one is the COST266 network with 28nodes and 82 unidirectional links and their link range is from 201 km to 1293 km. The second one is the JANOS-US-CA network with 39 nodes and 124 unidirectional links and their link range is from 217 km to 1310 km.



(a) (b)

Figure 4.1 Experimental networks

As shown in Figures 4.1, we assume the nodes with red colour are core nodes with maximum capacity of 1600Gbit/s, and the other nodes are edge nodes with maximum capacity of 320Gbit/s. According to [50], a network node' maximum energy consumption is roughly equal to $C^{3/2}$, where C represents the node switching capacity (Gbit/s). Therefore, core and edge nodes' maximum power rate E_m are 64000 Watts and 5725 Watts respectively. For our energy model, the minimum power consumption E_0 is set as a quarter of E_m. Since sleeping mode consumes relatively small amount of energy [75], the sleeping mode power parameters E_s of core and edge nodes are set as 0.05 of their full power consumption.

For the energy consumption of links, we assume that those links connected to the core nodes (i.e., highlighted by blue colour) are high capacity links with maximum capacity 320Gbit/s, while the rest links with black colour have identical maximum capacity is 80Gbit/s. Based on [16], the maximum power consumption of a link can be calculated by using the formulas below:

$$\mathrm{E_{mxy}} = \epsilon * \mathrm{A_{xy}} \quad (1)$$

$$\mathrm{A_{xy}} = (\mathrm{d_{xy}} \ / \ 80km) + 2 \quad (2)$$

Where ϵ = 9Watts, $\mathrm{d_{xy}}$ is the distance between node x and node y. Hence, the $\mathrm{E_m}$ of links in the COST266 is between 40.6 Watts and 163.5 Watts, the maximum link power rate in the JANOS-US-CA is in the range of 42.5 Watts to 165.5 Watts. The minimum power rate E_0 and sleeping mode energy consumption E_s are 0.25 and 0.05 of E_m respectively. The Maximum network elements utilization α is a safe threshold for network operators, normally in the range of 0.5 to 0.9. In this thesis we set it is 0.8. By testing, when the value of capacity variable (ξ) is equal to 10, the value of energy and capacity are roughly in the same scale.

4.2 Case Study I : The COST266 Network

In this section, our models are implemented in the COST266 network. The performance of them is compared through different perspectives, such as energy consumption, capacity utilization and network devices' working status. Fig4.2 below shows the COST266 network topology.

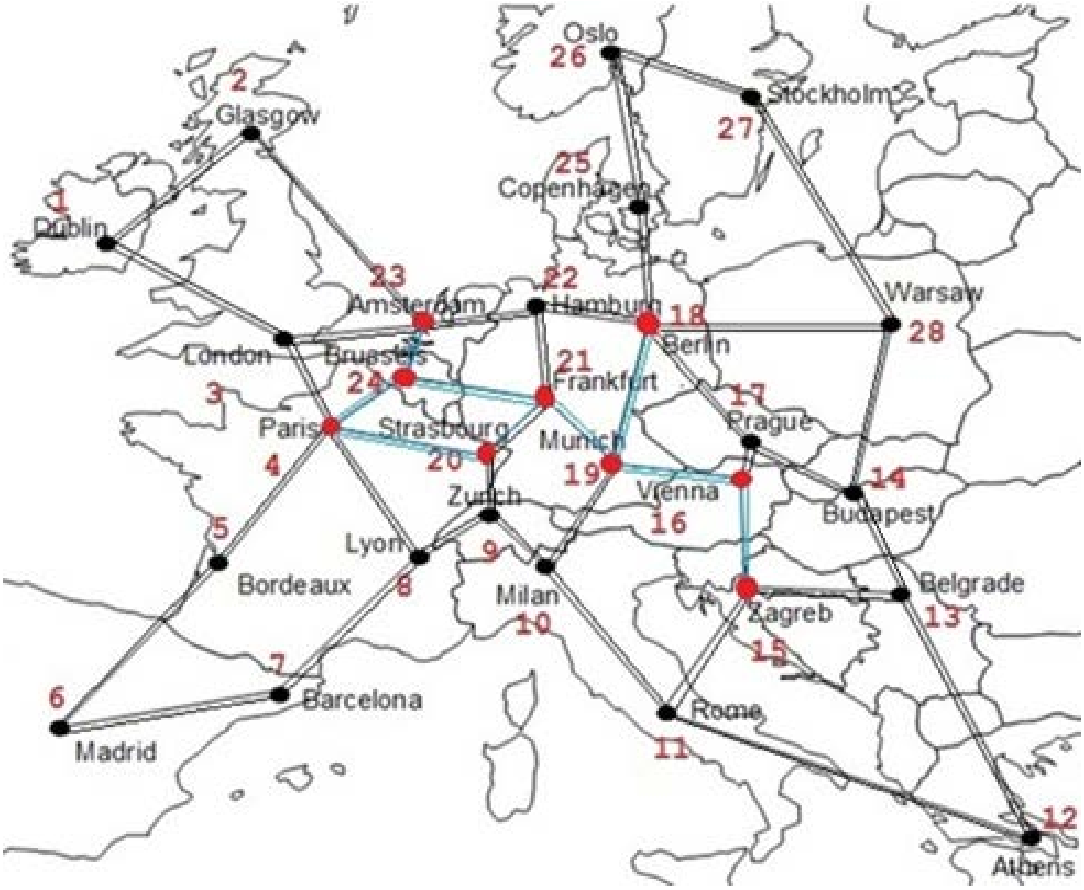


Figure 4.2 The COST 266 network topology

Table 4.1 Data traffic scenarios of 30, 60, 90,120Gbit in the COST 266

	30Gbit	60Gbit	90Gbit	120Gbit
Node1→Node 12	10	10	10	15
Node4→Node 28	10	10	10	15
Node6→Node 26	10	10	10	15
Node9→Node 27	0	10	10	15
Node11→Node 22	0	10	10	15
Node12→Node 2	0	10	10	15
Node14→Node 4	0	0	10	10
Node28→Node 23	0	0	10	10
Node26→Node 9	0	0	10	10

The traffic data in this case study is listed in Table 4.1. We set the traffic demands are between long distance nodes pair so that more optional and intermediate nodes and links can be involved. There are four scenarios of traffic demands, which are 30Gbit, 60Gbit, 90Gbit and 120Gbit, respectively.

4.2.1 Energy Consumption

Detailed results obtained for the three routing models are summarized in Table 4.2 below. It shows that links consume significantly less energy than nodes in both networks. This means that the energy saving is achievable by switching off links, but there is less contribution to the total energy saving than switching off the nodes. Moreover, we notice it is interesting that the total energy consumption of the EASBP model always higher than EABP 1:1. The reason for that is the total capacity saving need more energy usage to be compromised. In other word, for achieving the efficient capacity consumption using backup paths sharing, the primary paths of traffic demands are need to be disjointed, therefore more nodes and links are turning into working mode which causes energy expenditure to rise significantly. Moreover, EABP 1+1 consumes more power than the other two in every scenario of traffic demands.

Table 4.2 Energy consumption in Watts for Links and Nodes of different models in various connect requests of the COST266

		Connect Requests = 30Gbit	Connect Requests = 60Gbit	Connect Requests = 90Gbit	Connect Requests = 120Gbit
EABP 1+1	Links	1311.1	2023.6	2510.3	3183.2
	Nodes	129081	159816	190551	255394
	Total	130392.1	161839.6	193061.3	258577.2
EABP 1:1	Links	674.1	1158.2	1686.5	1927.7
	Nodes	63063	100366	115733.5	131101
	Total	63737.1	101524.2	117420	133028.2
EASBP	Links	1147.5	1856.4	2215.2	2870.7
	Nodes	105709.4	137522	143017.5	152375
	Total	106856.9	139378.4	145232.7	155245.7

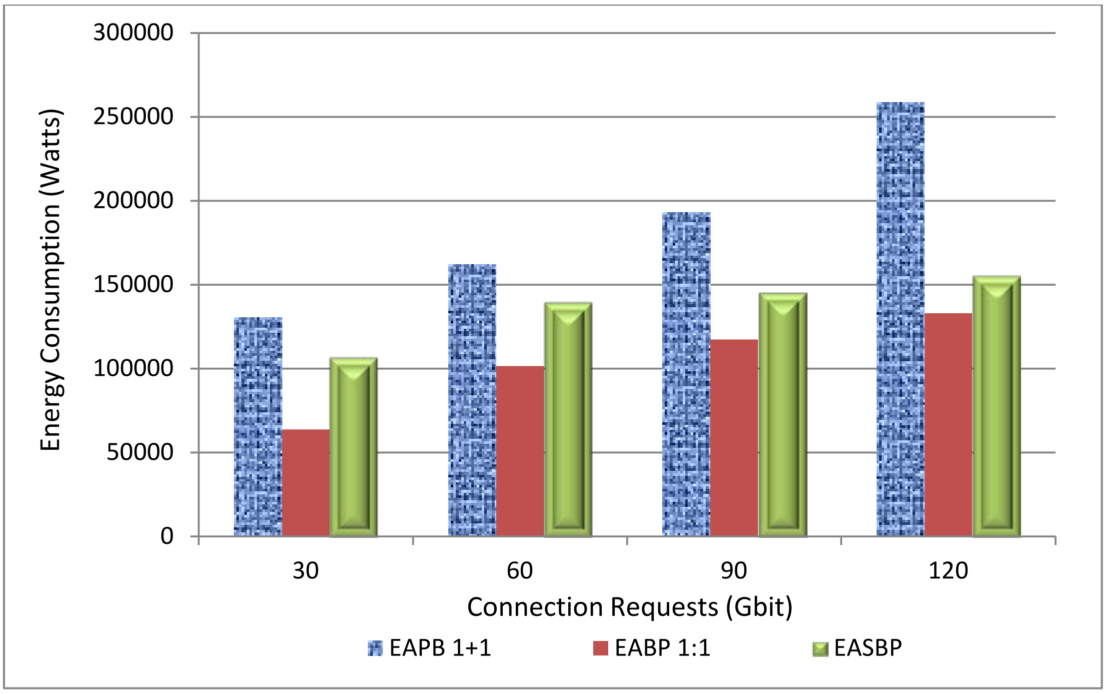


Figure 4.3 Total energy consumption vs. traffic scenarios for the three models in the COST266

Fig.4.3 above gives a graphic view of the behaviours of total energy consumption of the three models according to various traffic demands in COST266. It clearly shows that EABP 1+1 model always consumes more power compared with the other two models. The main reason is that EABP 1+1 doesn’t have sleeping technology. In addition, EABP 1:1 is the most energy efficient model among the three. Because it can switch backup resources into sleeping mode, and yet not need to disjoint primary path for some connection requests to achieve backup resource sharing. Furthermore, along with the increase of connection requests, there is a trend that the gap of energy consumption between EABP 1:1 and EASBP is shortened. It is because when traffic demands increase to certain amount, more nodes will be working state and less can be switch off or sleep, thus the advantage of EABP 1:1 on energy saving is not so obvious compares to EASBP.

From the findings above, we come to the following three conclusions: Firstly, EABP 1+1 is the most energy-hunger model in the three energy aware survivable routing models. Because EABP 1+1 is the only model hasn't applied sleeping technology, therefore it confirms that sleeping mode is a promising approach to reduce energy cost. The main difference between EABP 1+1 and EABP 1:1 is that the latter's backup paths can be switched into sleeping mode while the former's backup paths are always occupied for transmitting exactly the same data as primary path. Therefore by comparing EABP 1+1 and EABP 1:1, we will see how much energy can be saved by sleeping mode. In COST266, when traffic demand is 30Gbit, the energy usage of EABP 1:1 is 48.8% of that of EABP 1+1. Therefore, sleeping mode could save up to half of power expenditure in this topology.

Secondly, EABP 1:1 algorithm is our most energy efficient model due to the energy aware routing, energy consumption rating and sleeping mode strategies. By comparing with the traditional approach, the energy saving figure can be found. The traditional telecommunication routing strategy, i.e. Multi Commodity Flow (MCF) algorithm, is that energy consumption is independent with traffic loads [58] and is trying to balancing the traffic as evenly as possible on the network link [59] for the consideration of network survivability. In other word, the tradition MCF algorithm is trying to get more links and nodes involved in order to lowering the utilization level, and it doesn't have energy scaling strategy and sleeping mode. Therefore, in our two networks, we assume MCF sets every link and node into working status with full power. Hence, by calculating 28 nodes and 82 links working on full power, we can get the energy consumption of the MCF is 692852 Watts in the COST266. Compares to the worst-case scenario, our most energy efficient model – EABP 1:1 could save up to 90% of power expenditure when connect requests are 30Gbit .

Last but not least, when traffic demands increases, the value of energy consumption of EASBP will draw near to that of EABP 1:1. In other words, when traffic demands of network is high, the advantage of EABP 1:1 will become less obvious compared with EASBP on energy saving because more and more network elements have to be switched on to support various traffic demands .

In summary, the nodes can consume significantly more energy than links, therefore switching off or sleeping unnecessary nodes could contribute to more energy saving than that of links. In addition, sleeping technique is a promising approach to reduce energy wasting, it could save up to half of power expenditure in certain network topology and traffic demands. Moreover, by comparing with the traditional MCF algorithm, our most energy efficient model i.e., EABP 1:1 could save up to 90% of energy cost when network is lightly loaded. This is due to combinational using of energy aware routing, energy consumption rating strategy and sleeping mode technology. Finally, when traffic demands in network is high, the advantage of the EABP 1:1 will become less obvious compared to the EASBP on energy saving.

4.2.2 Capacity Consumption

In this session, we will look into the capacity usage requirements of the three algorithms. The Fig.4.4 below reveals the difference of their capacity usage behaviour in the topology of COST266.

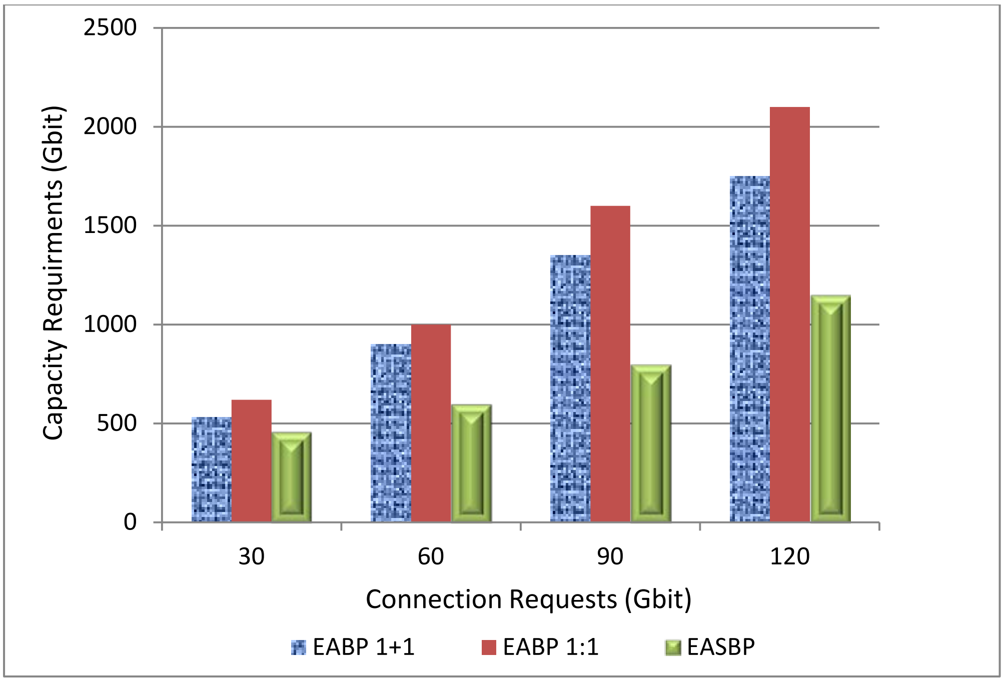


Figure 4.4 Total capacity consumption vs. traffic scenarios for the three models in the COST266

It can be seen from the above bar graph that EABP 1:1 shown as red bars always consumes more capacity than the other two models. It shows that more energy saving requires more capacity to be sacrificed. For minimizing the total energy consumption, EABP 1:1 model tends to reserve the backup path in existing sleeping links and nodes, which may need to detour primary or backup route, which causes the increasing of the total amount of capacity usage. As for EABP 1+1 shown in blue, it doesn't apply sleeping mode, hence it will select the shortest path for both primary and backup paths in order to get less network devices allocated. This is why it needs less capacity than EABP 1:1. For EASBP, it will search for potential sharable backup paths for traffic flows to save capacity usage, which makes it as the most capacity aware model among the three. Furthermore, it is noticeable that the gap between red bar and green bar, which represent EABP 1:1 and EASBP, are widened along with the increasing of connection requests. This is because along the traffic requests increase, there are more sharable resources. In detail, the capacity consumption of EASBP is approximately 63% to the EABP 1:1 when connection requests is equal to 60Gbit, then this value drops to about 53% when requests increase to 120Gbit.

In summary, by analysing the three models' capacity performance in the COST266 topologies, two conclusions can be reached. Firstly, EABP 1:1 model consumes more capacity among the three, because it needs to use relatively more capacity to achieve energy saving. Secondly, along with the traffic demands go up, the capacity consumption gap between EABP1:1 and EASBP become lager. In other words, as the traffic demands increase, the advantage of EASBP becomes even more noticeable.

4.2.3 The State of Network Elements

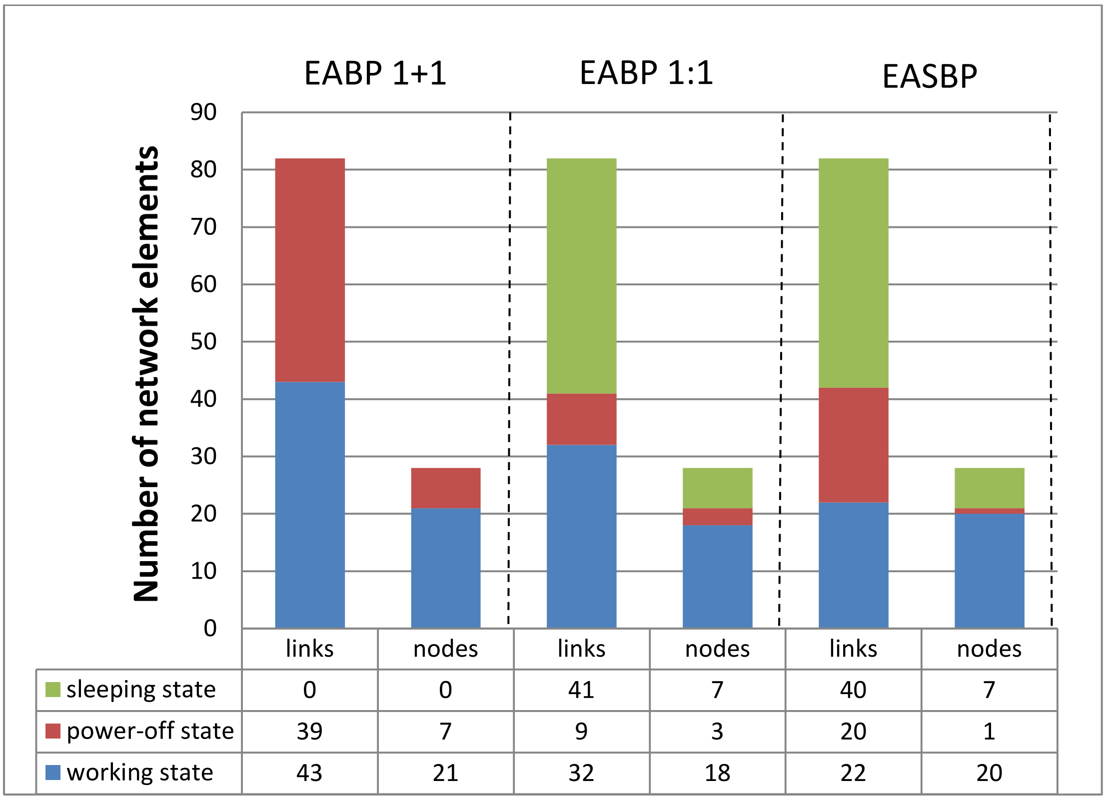


Figure 4.5 The state of Network elements when connection requests = 120Gbit in the COST266

When the traffic demands are relatively large, the states of network elements (i.e., links and nodes) are shown in Fig.4.5 above. It is interesting to see that EABP 1:1 is trying to switch more nodes into sleeping or power-off state to achieve energy saving, because of nodes consume much more energy compared to that of links. EABP 1:1 has 10 nodes working in low energy consumption status (either in power-off or sleeping), while EABP 1+1 and EASBP have 7 nodes and 8 nodes respectively. That's the reason why EABP 1:1 is the most energy efficient model among the three.

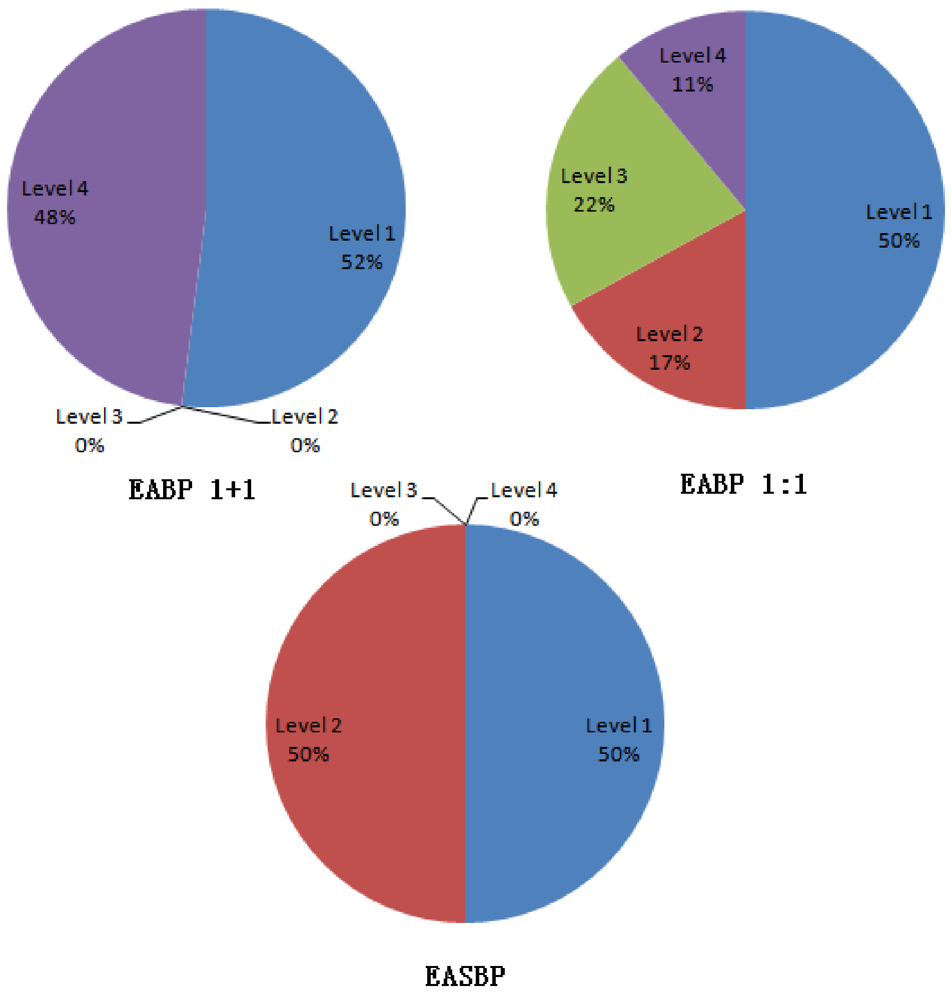


Figure 4.6 The working level of nodes of different models when connection requests = 120Gbit in COST266

Fig.4.6 above illustrates the energy level of working nodes in the three models when connection requests equal to 120Gbit. It shows that EABP 1+1 has 48% of nodes which are working on highest level, while EABP 1:1 has 22% nodes working on the third level and 11% nodes on the fourth level. These highly loaded nodes may become obstacles when network's traffic demands increase further. On the other hand, the EASBP model has no nodes working on the third and the highest level, which indicates that EASBP has much better network capacity when the traffic demands are becoming larger to the former two models.

4.3 Case Study II: The JANOS-US-CA Network

In this section, we will implement the three models in a more complex topology – the JANOS-US-CA network as shown in Fig4.7 below. Compared with the COST266 network, it has more nodes and links. Moreover, for the core nodes, it has more directions to route traffic flows. The goal of this case study is to find out whether the models act similarly as in the COST266. Their performances are compared through energy consumption, capacity utilization and network devices' working status.

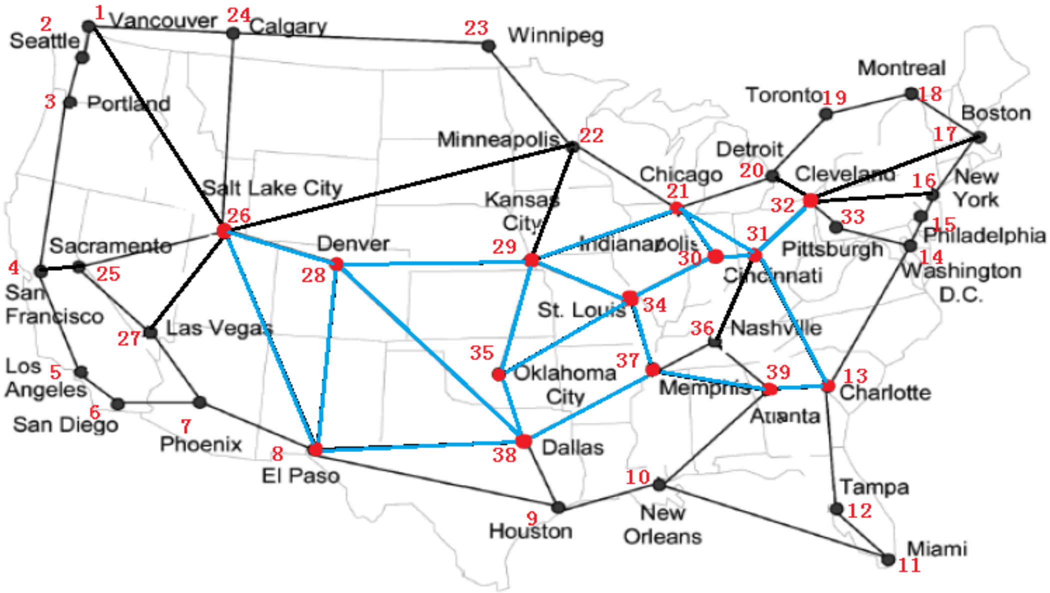


Figure 4.7 The JANOS-US-CA network topology

Table 4.3 Data traffic scenarios of 30, 60, 90,120Gbit in the JANOS-US-CA

	30Gbit	60Gbit	90Gbit	120Gbit
Node 1 → Node 11	10	10	10	15
Node 4 → Node 18	10	10	10	15
Node 7 → Node 17	10	10	10	15
Node 9 → Node 23	0	10	10	15
Node 12 → Node 2	0	10	10	15
Node 13 → Node 25	0	10	10	15
Node 16 → Node 27	0	0	10	10
Node 22 → Node 6	0	0	10	10
Node 21 → Node 8	0	0	10	10

The traffic data in this case study is listed in Table 4.3. We set the traffic is flowing between long distance nodes pair so that more optional and intermediate nodes and links can be involved. There are four scenarios of traffic demands, which are 30Gbit, 60Gbit, 90Gbit and 120Gbit, respectively.

4.3.1 Energy Consumption

Table 4.4 below gives the detailed results obtained for the three routing models in the JANOS-US-CA network. Similar to the result of the COST266, it shows that links consume significantly less energy than nodes in both networks. This means that switching off nodes contributes far more than switch off links to overall system energy saving. In addition, EABP 1+1 consumes more power than the other two in every scenario of traffic demands due to it doesn’t have sleep function. Besides, EABP 1:1 is the most energy efficient model. It is because that it has sleeping mode and doesn’t need to consider backup sharing. Moreover, EASBP model always need more energy than the EABP 1:1 model. The reason for that is the total capacity saving need more energy usage to be compromised.

Table 4.4 Energy consumption in Watts for Links and Nodes of different models in various connect requests of the JANOS-US-CA

		Connect Requests = 30 Gbit	Connect Requests = 60 Gbit	Connect Requests = 90 Gbit	Connect Requests = 120 Gbit
EABP 1+1	Links	2180.4	3162	3387.6	4305.6
	Nodes	136594.5	159138	184652.5	222792.8
	Total	138774.9	162300	188040.1	227098.4
EABP 1:1	Links	1009.2	1856.4	2244	3084.5
	Nodes	96072	117522	132889.5	159319.7
	Total	97081.2	119378.4	135133.5	162404.2
EASBP	Links	1808.5	2572	3115.2	4067.5
	Nodes	118870	143594.5	154654	176569
	Total	120678.5	146166.5	157769.2	180636.5

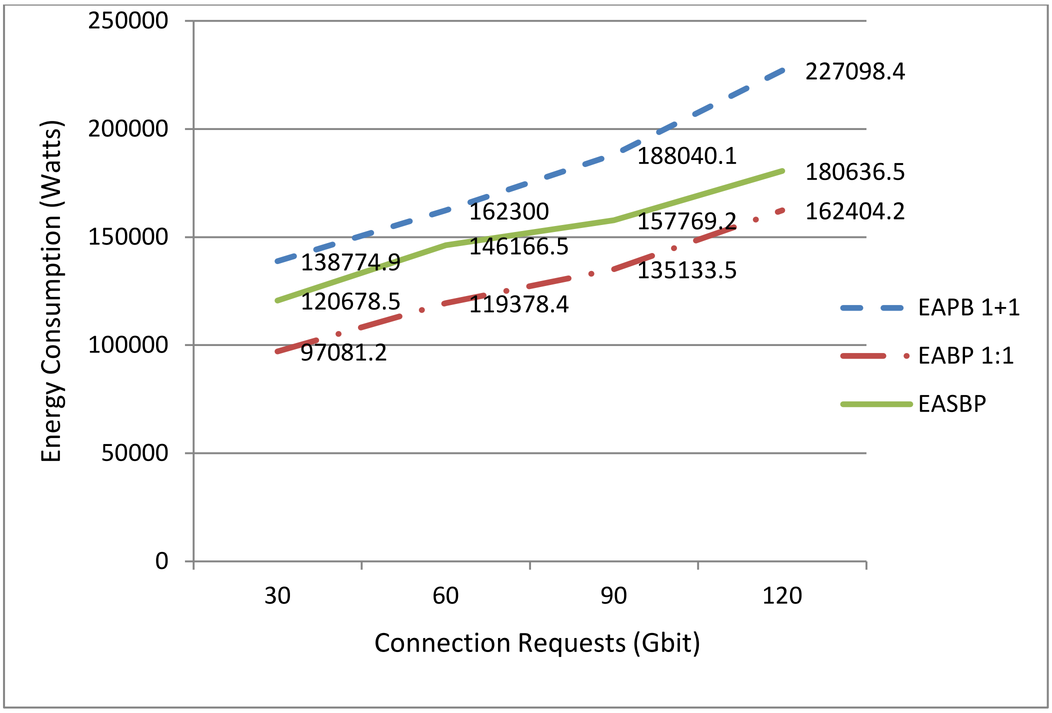


Figure 4.8 Total energy consumption vs. traffic scenarios for the three models in the JANOS-US-CA

Fig.4.8 demonstrates the behaviours of total energy consumption of the three models in four connection requests scenarios. It clearly shows that EABP 1+1 model which shown as blue dash line, always above the other two models. The main reason is that EABP 1+1 doesn't have sleeping technology, hence it doesn't have good energy saving performance compared with EABP 1:1 and EASBP. In addition, the red dot line is always at the bottom, which reflects EABP 1:1 is the most energy saving model in every scenarios. Because it can switch backup resources into sleeping mode, and yet not need to disjoint primary path for some connection requests to achieve backup resource sharing. Furthermore, along with the increase of traffic demands, the green solid line is getting close to the red dot line. In other words, when traffic demands are large, the advantage of EABP 1:1 on energy reduction will be less noticeable than EASBP.

From the findings above, we can draw the following three conclusions: Firstly, EABP 1+1 consumes the most energy among the three energy aware survivable routing models. It confirms that sleeping mode is a promising approach to reduce energy cost due to EABP 1+1 is the only model hasn't applied sleeping technology. As we know the only difference between EABP 1+1 and EABP 1:1 is the latter one with sleeping mode while the former without it. Therefore by comparing EABP 1+1 and EABP 1:1, we will see how much energy can be saved by sleeping mode. In JANOS-US-CA topology, EABP 1:1 can save up to 30.1% compared with EABP 1+1 when traffic demand is 30Gbit.

Secondly, EABP 1:1 algorithm is the most energy efficient model due to the combination usage of energy aware routing, energy consumption rating and sleeping mode strategies and yet not consider capacity saving. By comparing with the traditional approach MCF, the figures of energy saving can be found. We assume the MCF algorithm sets every link and node into working status with full power, because it does not have sleeping mode and energy scaling strategy. Hence, by calculating 39 nodes and 124 links working on full power, we can get the energy consumption of the MCF is 1054302.6 Watts in the JANOS-US-CA network. Compares to the worst-case scenario, our most energy efficient model – EABP 1:1 is around 10% of its energy needs when traffic demands are 30Gbit.

Last but not least, along with traffic demands increasing, the value of energy consumption of EASBP is gradually drawing near to that of EABP 1:1. In other words, when traffic demands of network is high, the advantage of EABP 1:1 will become less obvious compared with EASBP on energy saving.

In summary, by implementing our models in a more complex network, we obtained similar experimental results as the first case study. First of all, the nodes consume significantly more energy than links, therefore switching off unnecessary nodes or sleeping low utilization nodes could be an effective approach to achieve energy reduction than switching off links. In addition, sleeping technology is a promising approach to green networks; it could save up to 30.1% of power expenditure in JANOS-US-CA network. Moreover, by comparing with the traditional MCF algorithm, our most energy efficient model--EABP 1:1 could save up to 90% of energy cost when traffic demands of network is low. Finally, along with the increase of traffic demands, the advantage of the EABP 1:1 will become less obvious compared to the EASBP on energy reduction.

4.3.2 Capacity Consumption

In this session, we will compare the capacity consumption of the three models. The Fig.4.9 below reveals the difference of their capacity usage behaviour in the topology of the JANOS-US-CA. Similar to the findings in the COST266, it can be seen that the red line which represents EABP 1:1, always higher than the others. It means the EABP 1:1 model consumes more capacity to achieve more energy saving. It tends to reserve the backup path in existing sleeping links and nodes, which may need to detour primary or backup route, which causes the increasing of the total amount of capacity usage. EABP 1+1 shown as blue line always in the middle, it has better performance than EABP 1:1 on capacity saving, because it selects the shortest path for both primary and backup paths since without sleeping mode. As for the green line EASBP, it is the best model to reduce capacity usage due to its ability to share backup resources. Furthermore, it is interesting that the gap between EABP 1:1 and EASBP are widened along with the increasing of connection requests. The capacity consumption of the EASBP is approximately 72% to the EABP 1:1 when connection requests is equal to 30Gbit, this figure then drops to about 54% when requests increase to 120Gbit.

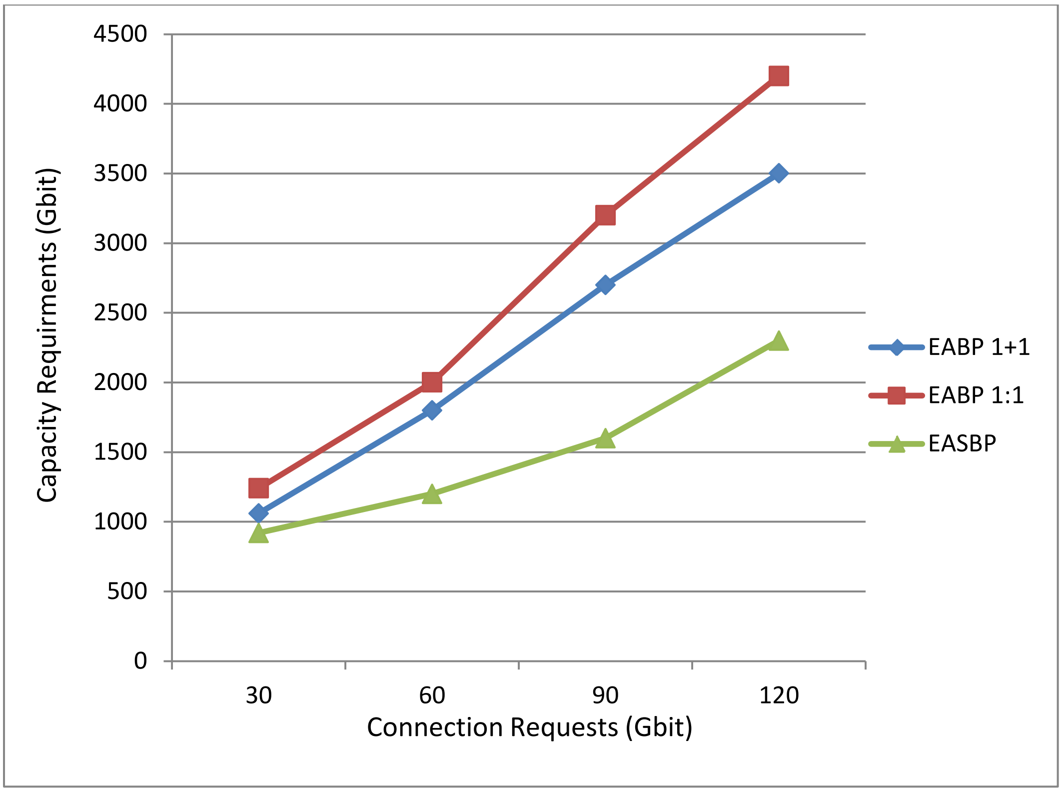
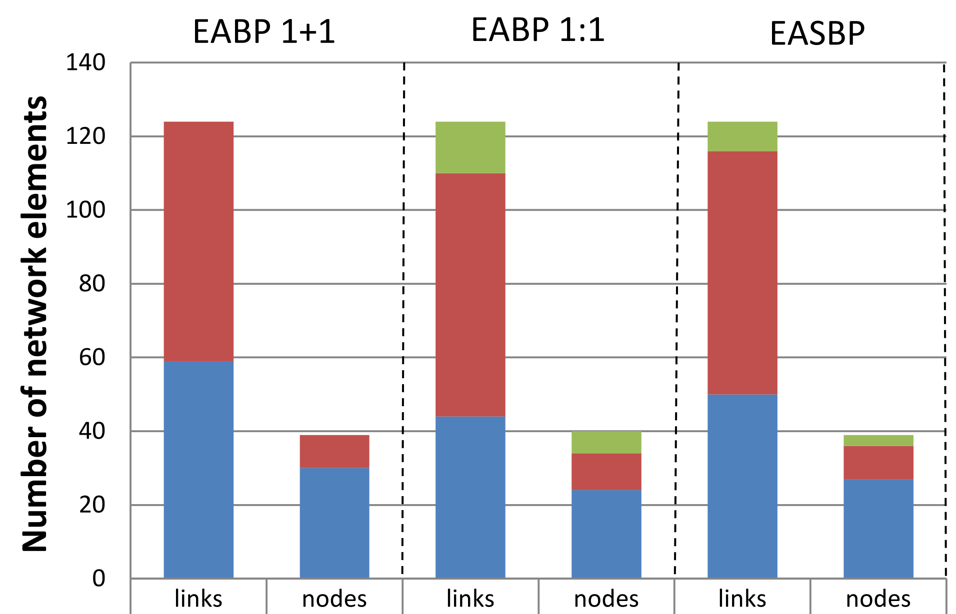


Figure 4.9 Total capacity consumption vs. traffic scenarios for the three models in the JANOS-US-CA

In summary, we can draw two conclusions by analysing the three models' capacity performance in the JANOS-US-CA network topology. Firstly, EABP 1:1 model is relatively thirsty for capacity among the three, because it fiercely aggregates traffic flows which may lead to traffic detour, so as to increase the requirement of capacity. Secondly, along with the rise of traffic demands, the capacity consumption gap between EABP1:1 and EASBP widened. In other words, when the traffic demands are large, the advantage of EASBP becomes even more significant than EABP 1:1.

4.3.3 The State of Network Elements

In this section, we look into how the three models' nodes and links worked in the JANOS-US-CA network.



	links	nodes	links	nodes	links	nodes
sleeping state	0	0	14	6	8	3
power-off state	65	9	66	10	66	9
working state	59	30	44	24	50	27

Figure 4.10 The state of Network elements when connection requests = 120Gbit in the JANOS-US-CA

Fig.4.10 above shows the states of network elements of our models when the traffic demands is 120Gbit. Similarly to the case study 1, EABP 1:1 is trying to switch more nodes into sleeping or power-off state. Because nodes consume much more energy than that of links, so most of the energy saving comes from shut-down or sleeping nodes. EABP 1:1 has turned 10 nodes off and switched 6 nodes into sleeping mode, which means it has 16 nodes in low energy consumption status. On the other hand, EABP 1+1 and EASBP have 9 and 12 nodes in low energy consumption status respectively.

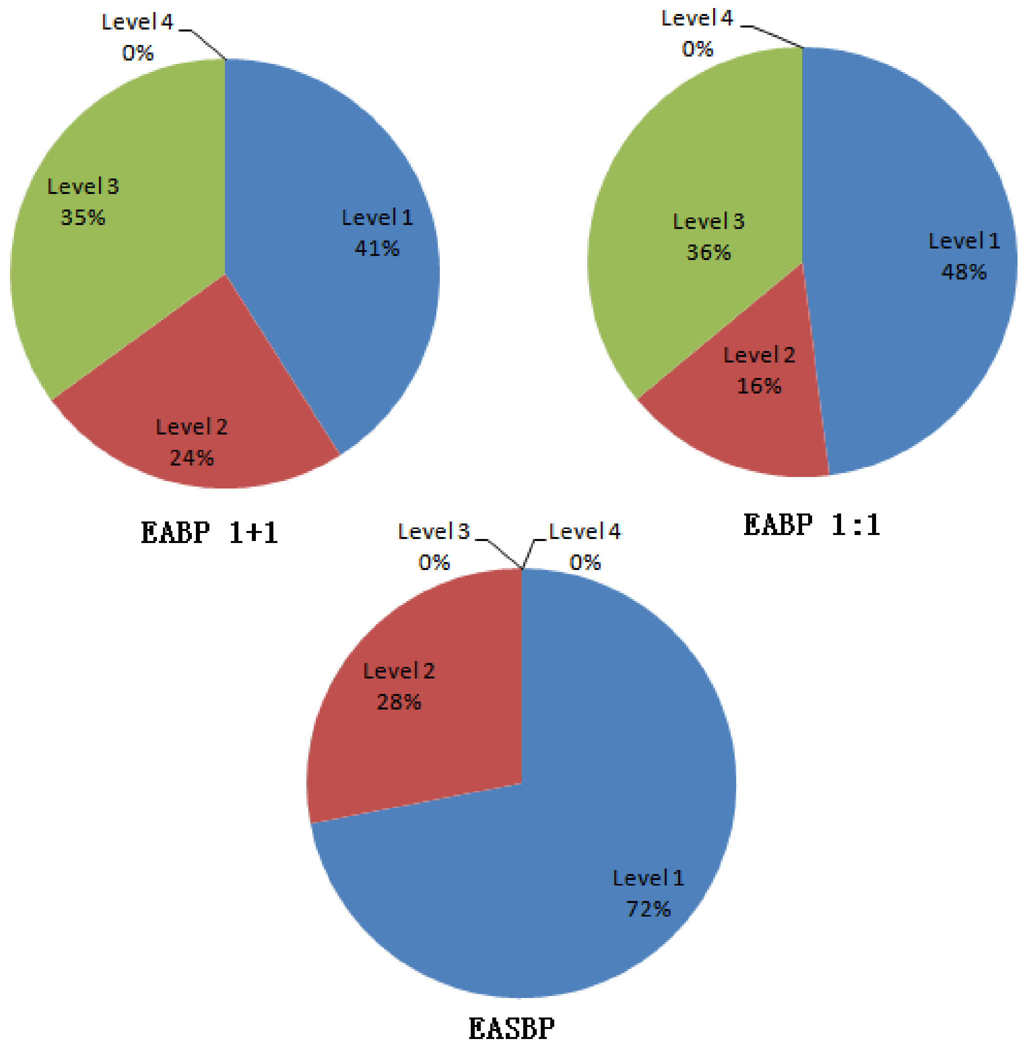


Figure 4.11 The working level of nodes in different models when connection requests = 120Gbit in the JANOS-US-CA

Since nodes use significantly more energy than links, we further explore those working nodes' load level. Fig.4.11 above illustrates the energy level of working nodes in the three models when connection requests are 120Gbit. As can be seen from Fig.4.11, EABP 1+1 and EABP 1:1 both have more than one third of working nodes working on third level, while EASBP has no nodes working on high energy level. This result indicates EASBP has better capacity usage than the other two.

4.4 Summary

In this chapter, we implemented the three energy aware survivable routing models in two networks, and then their performance are analysed and compared through different perspectives, such as energy consumption, capacity utilization and network devices' working status. The features of models in our two case studies are very similar, which means the three models perform consistently in different network topologies. The numerical results confirm that, for a given static traffic demand and topology, it is possible to turn off some redundant network nodes and links but to still guarantee network survivability between sources and destinations, while achieving overall energy efficiency of the network. In addition, sleeping mode is a promising approach to reduce energy expenditure. By comparing EABP 1+1 and EABP 1:1, the sleeping mode technology could save half of the total energy consumption. Moreover, EABP 1:1 is our most energy efficient model by using of energy aware routing, energy consumption rating strategy and sleeping mode technology, and no taking capacity saving into account. Compared with the traditional MCF algorithm, it could save up to 90% of energy cost when network is lightly loaded. Last but not least, the EASBP model has remarkable advantage among the three: it consumes significantly less capacity but a small increase in energy expenditure, especially under the condition of large traffic demands. Therefore, EASBP is the most promising model to tackle the trade off between energy consumption and network survivability.

Chapter 5

Simulation of Energy Aware Survivable Routing Models in TOTEM Toolbox

As CPLEX + OPL development environment can only produce numerical results, it is more useful and informative to implement the three models in a network simulator, which can better visualize the results and also show how the models work. For visualizing the results, we have developed and embedded the three energy aware survivable routing models into a simulation toolbox – TOTEM [76], which stands for TOolbox for Traffic Engineering Methods. In this chapter, we firstly present how we develop TOTEM to primarily integrate our new three energy aware survivable routing models in detail. Then the simulation results are analysed and compared.

5.1 Integrate Energy Aware Survivable Routing Models into TOTEM

The TOTEM toolbox has been designed to facilitate the integration of new algorithms by providing different generic network simulation components. It provides topology information (nodes, links, LSPs etc.) to the algorithm to be integrated. It also provides multiple scenarios execution functionalities. The architecture of TOTEM is shown in Fig.5.1 below.

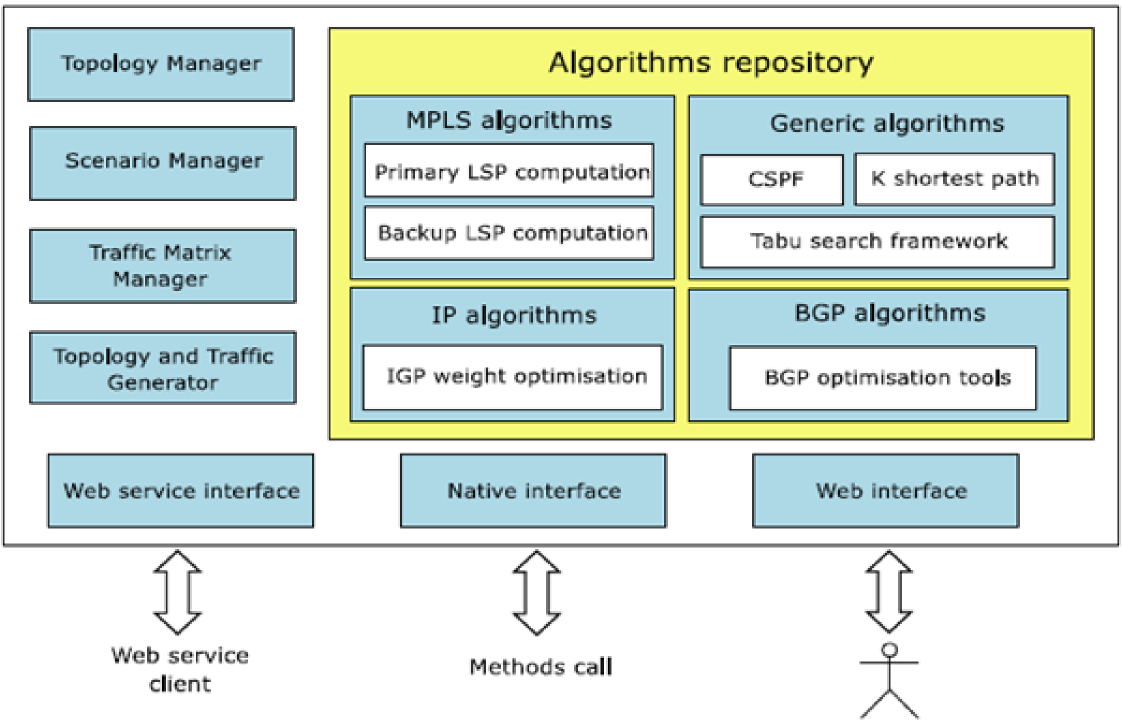


Figure 5.1 TOTEM architecture [8]

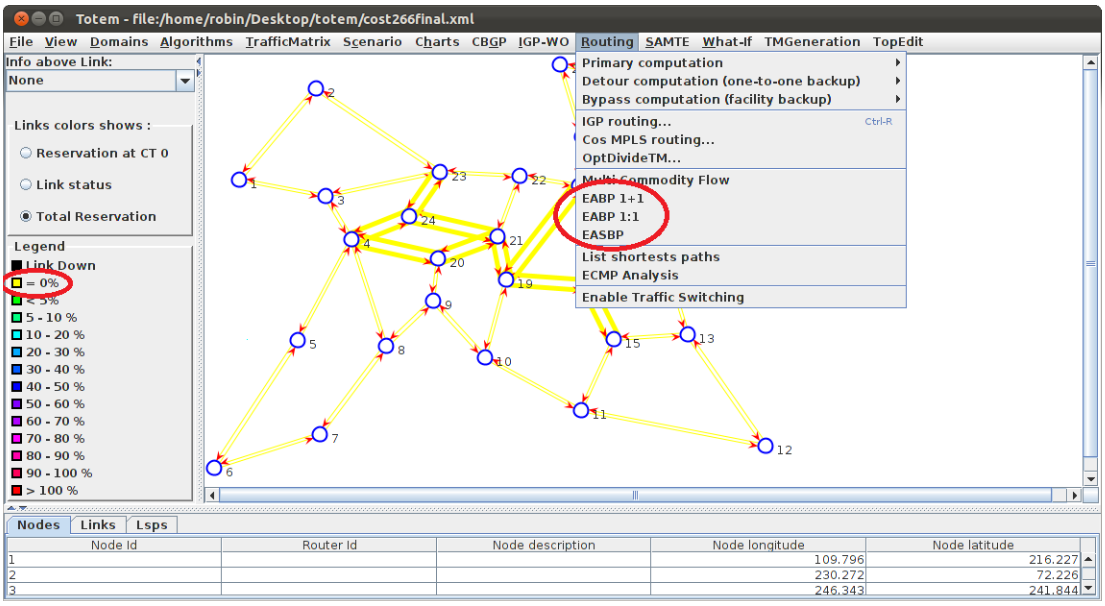


Figure 5.2 Modification on TOTEM GUI

In our work, we have primarily integrated our three energy aware survivable routing algorithms [5] in TOTEM. We have modified Topology Manager, Algorithms Repository and Native Interfaces. Firstly, we have modified its GUI file, such as adding a drop-down list for our three algorithms, and also introducing a new link status of turn off, which is indicated by yellow colour when the utilization of these links is equals to zero (see Fig.5.2). In this condition, we assume these links have no loads which could be turned off. Then, we have built our ILP models using AMPL [77], which is an modelling language similar to OPL. These models are placed in totem\src\resources\modelAMPL, so that they can be called by TOTEM main function. The last step is to modify the Java core functions so that the models can be called, and the results can be transferred and interpreted into GUI to be visualized in diagram.

5.2 Simulation Results

For better visualizing the numerical results of the three routing models, we have conducted the simulation studies in TOTEM by using the same network topologies (i.e., the COST266 and the JANOS-US-CA network) and network parameters' configurations.

5.2.1 Link Utilization

In this section, we will show how our models worked in TOTEM with several topologies. Their link utilizations are compared with each other as well as with a TOTEM embedded algorithm – MCF, which we briefly introduced in previous chapter. The MCF is targeting to balance the traffic as evenly as possible on the network links, without considering energy saving and backup protection. Therefore, the links' utilization will be minimized; however it may cost more energy and does not have backup protection. There are two reasons we choose MCF to compare with our models:

(i): It is already embedded in TOTEM, quite easy to call this algorithm;

(ii):It is a traditional traffic engineering oriented routing algorithm in telecommunication industry and can be treated as a reasonable benchmark

The following sessions are organized as below. Firstly, the three models are validated in a simple network with 8 nodes in TOTEM. By using a simple traffic data assumption, the difference between these algorithms can be clearly visualized. Then the extensive simulation results for the COST266 and the JANOS-US-CA networks are presented.

5.2.1.1 Simulation in a simple 8 nodes network

For validating our energy aware survivable routing models in TOTEM, we firstly simulate them in a simple network as Fig.5.3 below, which has 8 nodes and 26 links. Each link has the maximum capacity of 1Gbit and there are two traffic flows with 400Mbits of traffic demand both from node 1 to node 8.

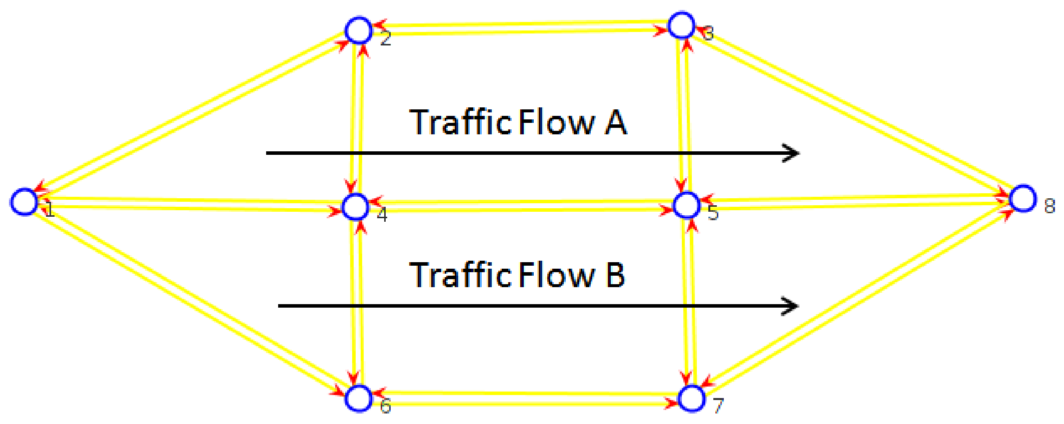


Figure 5.3 8 nodes experimental network

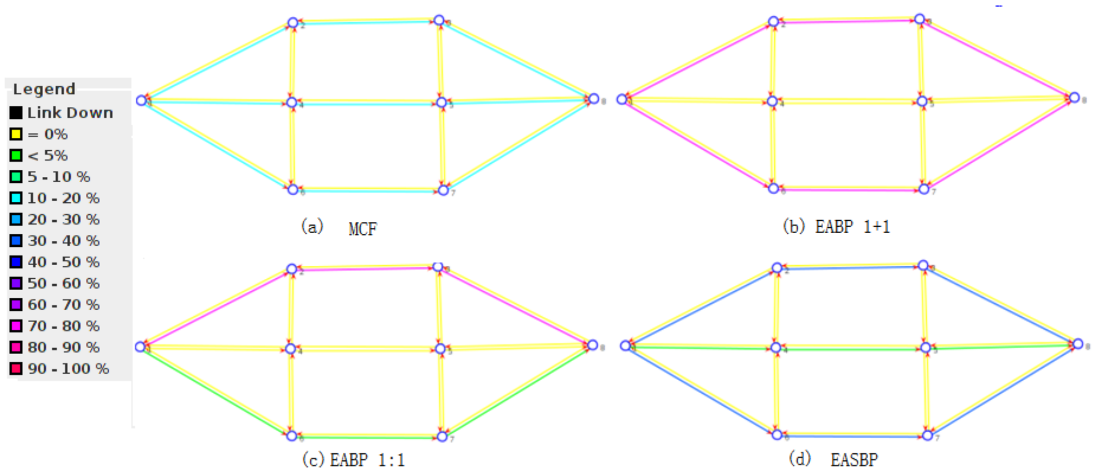


Figure 5.4 Simulation results of the four algorithms in an 8 nodes topology

The Fig.5.4 shows the simulation results of our three models as well as that of the MCF algorithm. In Fig.5.4 (c) and (d), we multiply the reserved bandwidths for backup path by a small factor (0.1) for better illustration. The purpose is to distinguish the backup paths from the primary path, otherwise the primary path and backup path will be seen as the same colour. It is only an experimental approach in order to check whether our models are correct or not.

From Fig.5.4 (a), we can see that the traditional MCF is trying to well balance the traffic load among links. Therefore, it divides the two traffic flows and transmits them diversely through three paths: 1-2-3-8, 1-4-5-8, and 1-6-7-8. Thus each link’s utilization of MCF algorithm is around of 26.6%.

The simulation result of EABP 1+1 is demonstrated in Fig.5.4 (b). The EABP 1+1 algorithm does not use sleeping mode technique, thus the traffic flow A and B will randomly select one of potential paths between1-2-3-8 and 1-6-7-8 as their primary route, and the other path as backup route respectively. Therefore, the path 1-2-3-8 and 1-6-7-8 will all transmit 800Mbits and the working link’s utilization is 80%.

While in Fig 5.4 (c) of EABP 1:1 algorithm, it can be seen clearly that the primary paths for flows A and B is the same i.e., 1-2-3-8 with red colour, their backup paths are reserved through 1-6-7-8 with green colour. The EABP 1:1 algorithm aggregates the two traffic flows into one primary working path, so that their backup path can be switched into sleeping mode to save energy.

The EASBP model is designed to achieve backup capacity sharing, and the primary paths for flows A and B need to be nodes disjointed, which means no single link/node overlapped in the primary working paths except the source and destination nodes. The simulation results showed in Figure 5.4 (d) confirmed that our energy aware shared backup protection model enforcing the shared backup path rules. The primary paths for traffic flows A and B is 1-2-3-8 and 1-6-7-8 respectively with the utilization rate of 0.4, and they are sharing the path of 1-4-5-8 as their backup path.

By validating our three models with a simple network topology and two traffic demands, we have confirmed that our models behave well under our expectations. Moreover, the different routing strategies and their results can be visualized in TOTEM.

5.2.1.2 Simulation in the COST266 Network

After validating the three models’ correctness in a simple network, we have conducted simulation studies of these three models in more complex topologies i.e., the COST266 and the JANOS-US-CA networks. All parameters of network configuration are identical to the previous chapter. We have chosen the large connection requests (120G) as our simulation traffic matrix. Moreover, the MCF algorithm is used here as a benchmark algorithm.

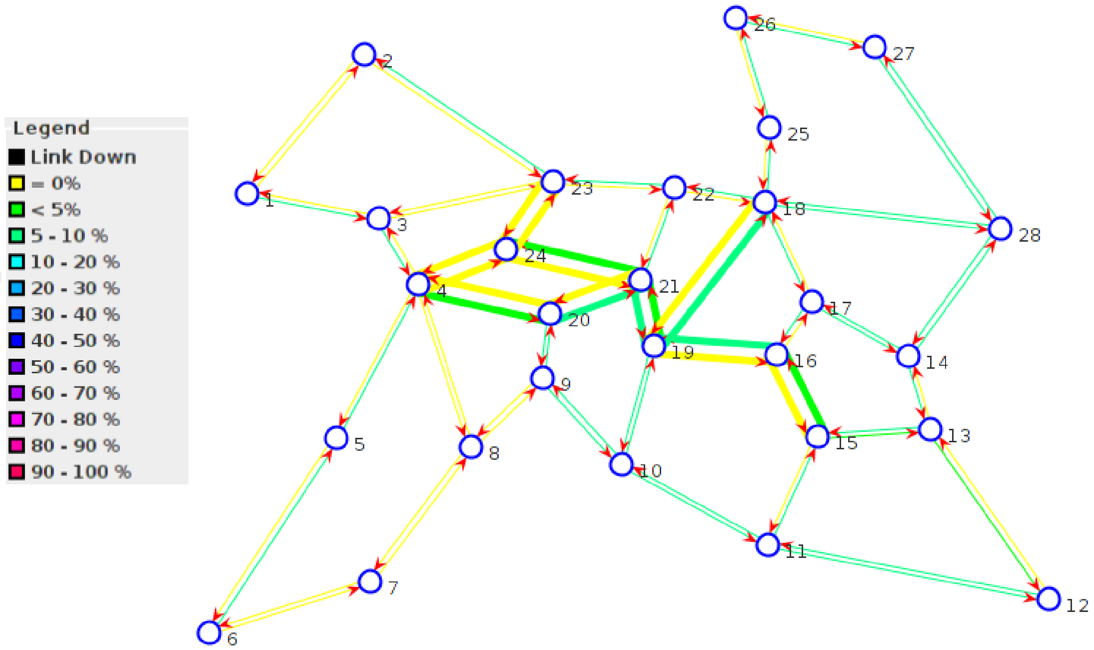


Figure 5.5 Simulation results of MCF in the COST266

The Fig.5.5 demonstrates the simulation results of the MCF algorithm in the COST266 network. The thick lines are the high capacity links with the volume of 320Gbit/s, while the thin lines are links with the capacity of 80Gbit/s. As we can see from the Fig.5.5 that the colours of links mostly are green or light green, which indicates that links are carrying very low traffic load (below 10%) when using the MCF algorithm. However, the MCF does not apply any energy aware strategy, which means all nodes in MCF are in working status. Thus MCF is a good model to balance the link utilization but sacrificing extra energy consumption for the diversity.

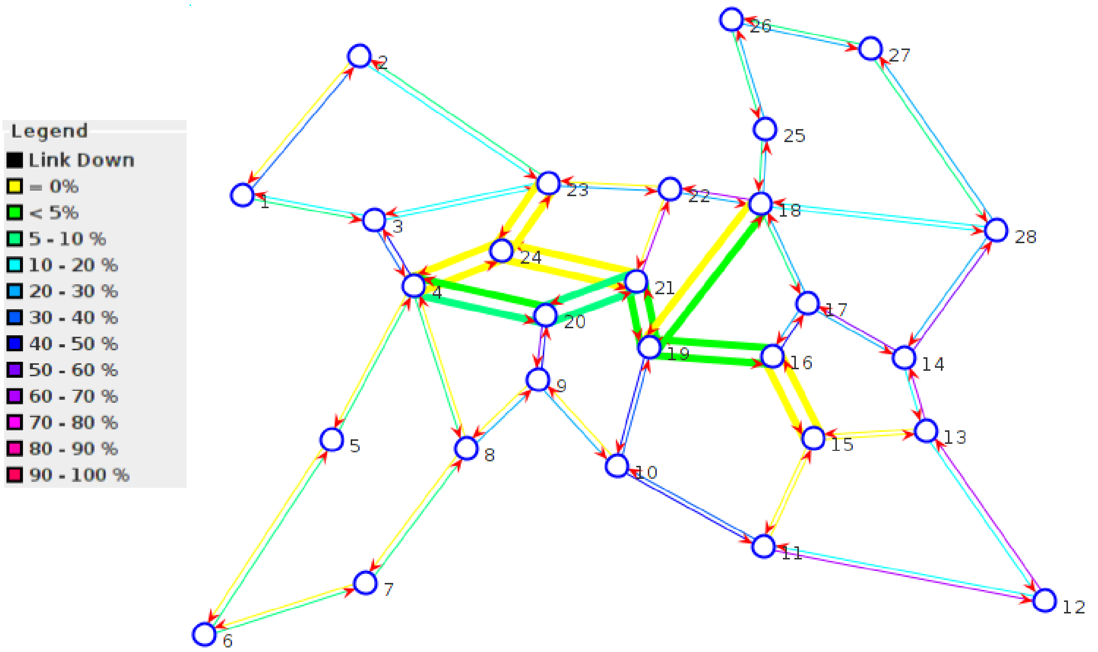


Figure 5.6 Simulation results of EABP 1+1 in the COST266

The simulation of EABP 1+1 can be found in Fig.5.6. Here we can see the node 24 and node 15 could be shut down, because all links connected to it are in yellow, which means no traffic loads. Compared with MCF, nearly half of the working links of EABP 1+1 are in higher utilization rate, shown in blue or purple. It may not be as advanced as MCF on balancing links' utilization, but by shutting two possible nodes down and applying energy consumption rating strategy, it can reduce considerable amount of energy than MCF.

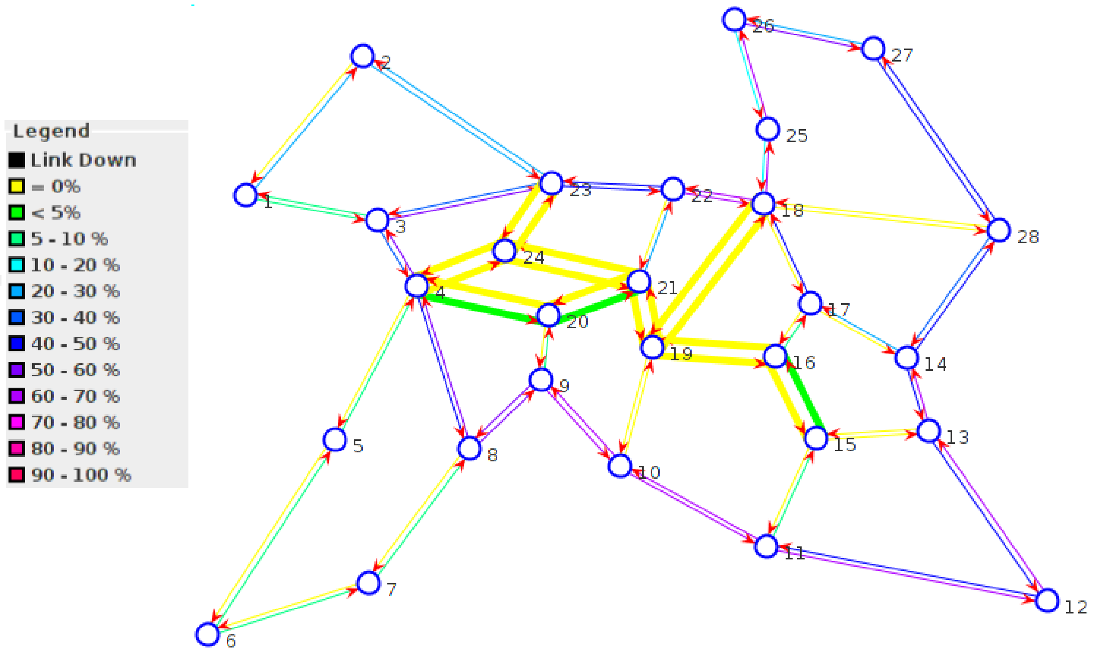


Figure 5.7 Simulation results of EABP 1:1 in the COST266

The EABP 1:1 model's simulation result is shown in Fig.5.7. Firstly, we notice that there are two nodes could be shut down, node 24 and node 19. Secondly, in the core of the network, most of the links have no traffic loads or in light loads, shown in yellow or in green. However, on the edge, its links almost formed a "purple ring" which indicates the links' capacity is highly utilized over 60%. The reason is that since the edge nodes are the terminals of traffic demands, most of the edge nodes and links have to be turned on, therefore EABP 1:1 tries to aggregate the traffic flows into the already working edge nodes and links. In other word, EABP 1:1 avoids as much as possible to turn on core nodes or links to save energy. It will turn off some of the core nodes and aggregate the backup capacity to the rest core nodes, which could be switched into sleeping mode.

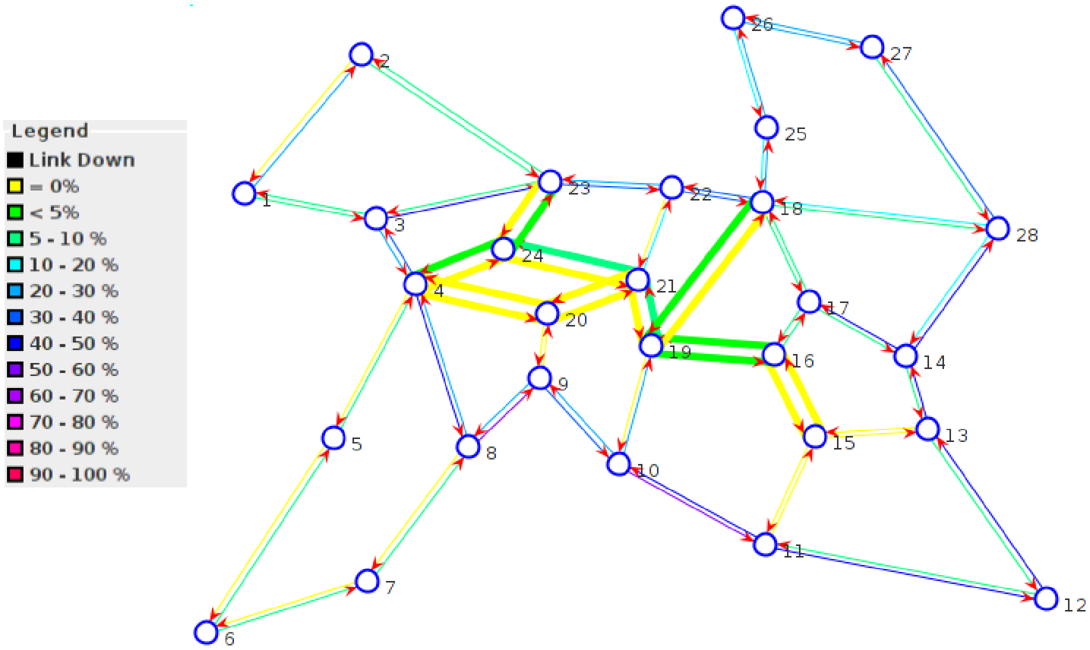


Figure 5.8 Simulation results of EASBP in the COST266

Fig.5.8 shows the situation of the EASBP algorithm simulating in the COST266 network. It also has two nodes could be shut down: the node 20 and node 15. Compares to EABP 1:1, most of the working links of EASBP has not reached high utilization levels. It can be seen that there are just few links in purple, which reflects EASBP has an advantage over EABP 1:1 on lowering links' utilization.

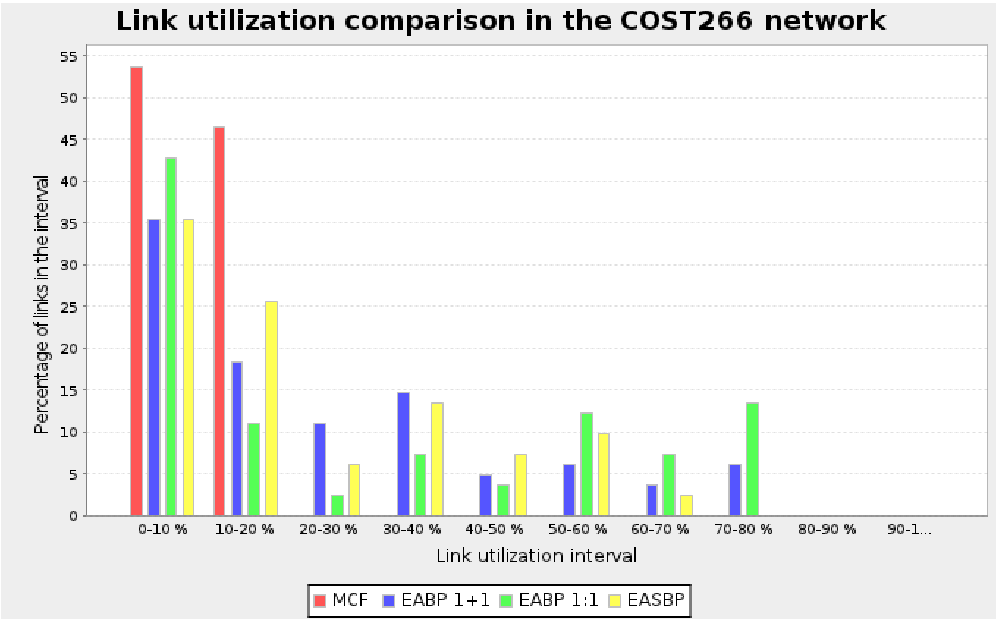


Figure 5.9 Link utilization distribution of the four models in the COST266

Moreover, the Fig. 5.9 above compares the link utilization of these four models' capacity behaviour. It can be seen that all the red bars which represent the MCF algorithm, are in the first two utilization intervals, which confirms that MCF is targeting to load balancing and thus no link goes over 20 percent of its capacity. While for EABP 1+1 represented as blue bars, there are more than 17 percent of its links reach 50% utilization or higher. This figure for EABP 1:1 is even worse, approximately 35% of its link in more than 50% utilization. However, EASBP shown as yellow bars has only 12% half loaded and no one link reaches utilization of 70%. The Fig.5.10 below is further illustrating the utilization comparison among the four models. It also showed that when links utilization is above 50%, EABP 1:1 highlighted with solid green line is above all other models, while EASBP (as purple line) is below the other two. This interesting finding again proves that EASBP has better performance of lowering links' utilization, while EABP 1:1 and EABP 1+1 aggregate traffic flows which increased the burden of links.

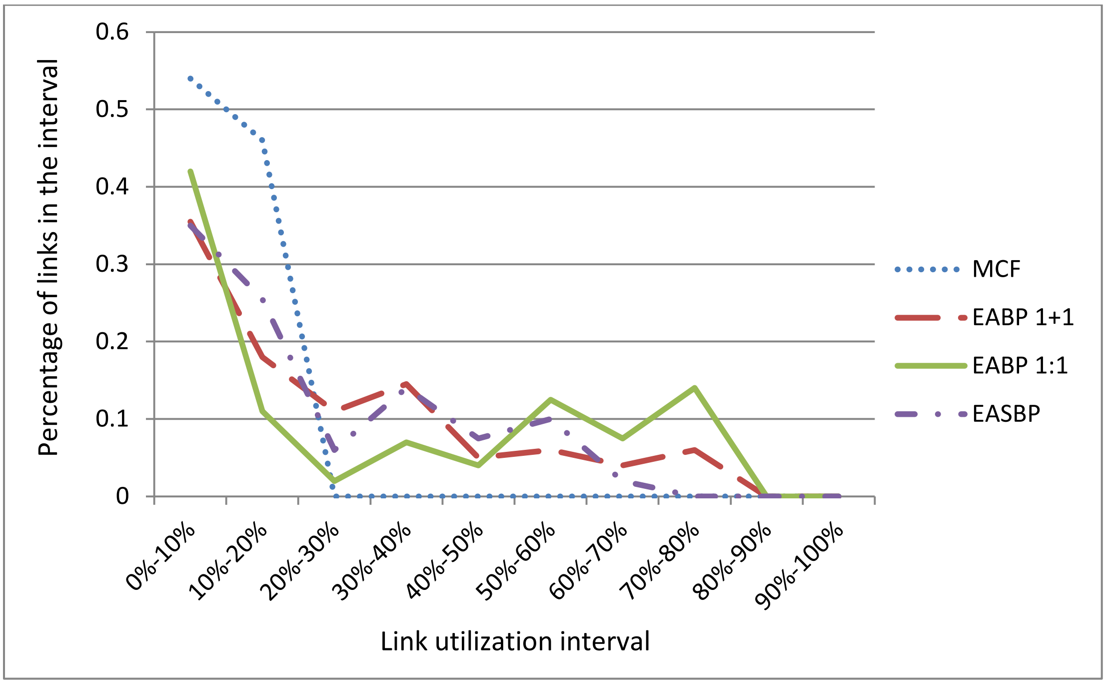


Figure 5.10 Link usage states of the four models in the COST266

From the overall findings in the COST266 network, we can draw three conclusions. Firstly, MCF has the best performance on lowering links' utilization. The reason for that is MCF sets most of the nodes and links in working state to share traffic load. Secondly, EABP 1:1 aggregates traffic flow into edge nodes and links, and avoids as much as possible to turn on core nodes or links to save energy. It is the most energy efficient model among the four, yet has the highest link utilization. Last but not least, the EASBP has the best performance of lowering links' utilization among our models.

5.2.1.3 Simulation in the JANOS-US-CA Network

After the simulation work in the COST266, we then implemented our models in a more complex network--the JANOS-US-CA. Compares to the COST266, the JANOS-US-CA has more nodes and more links. What's more, its core nodes have more potential paths to route traffic flows. All parameters of network configuration are identical to the chapter 4. The connection requests are 120G as our simulation traffic matrix. The following is the simulation results of our models in this more complex network and the bench mark algorithm MCF as well.

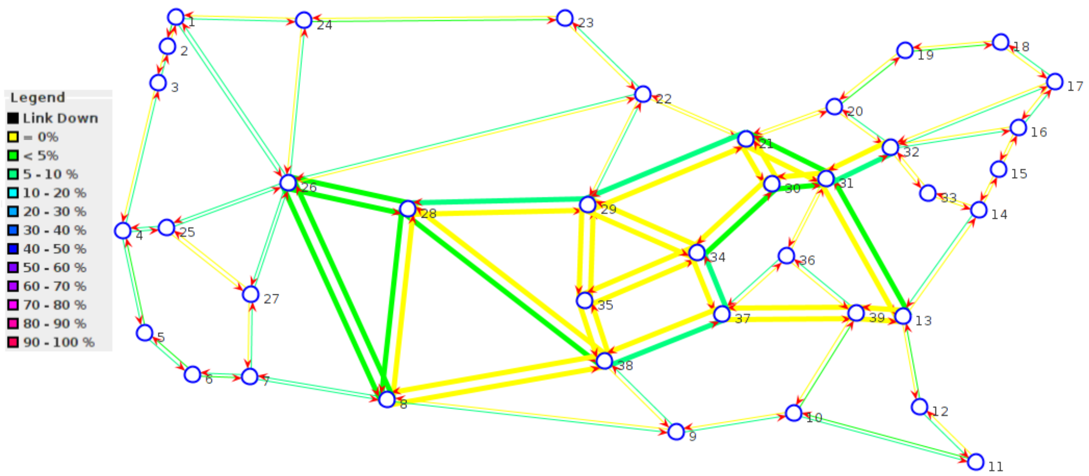


Figure 5.11 Simulation results of MCF in the JANOS-US-CA

Firstly, we investigate how the MCF works in the JANOS-US-CA network. As can be seen from Fig.5.11, the colours of working links are green and light green, which shows that links' utilization are below ten percent when using the MCF algorithm. However, most of node at least has one link has load, only node 35 has the possibility to be shut down. Thus the MCF algorithm achieves quite desirable link utilization of overall system by switching on most of devices.

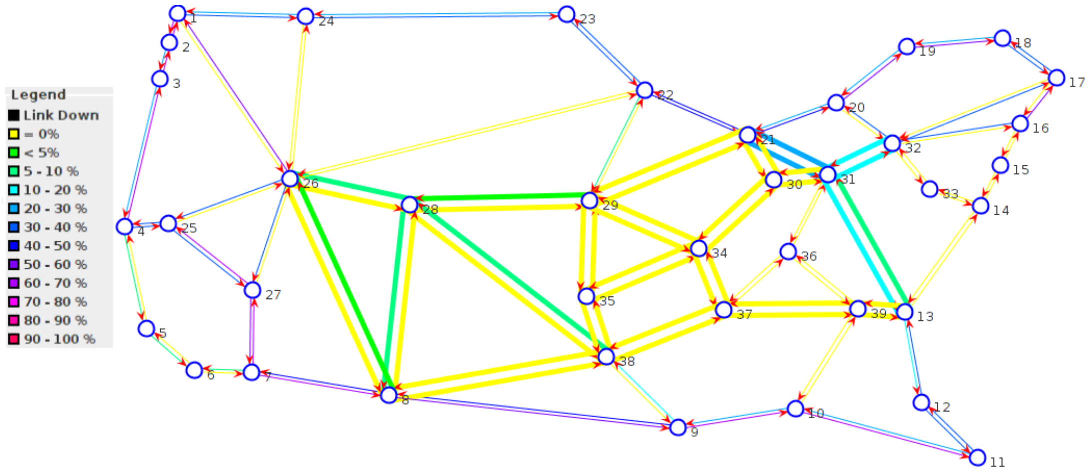


Figure 5.12 Simulation results of EABP 1+1 in the JANOS-US-CA

The simulation result of EABP 1+1 model can be found in Fig.5.12 above. It shows that there are nine nodes could be switch off, because all links connected to them have no traffic loads. Compares with MCF, most of the working links of EABP 1+1 are in higher utilization rate, which above 50% shown in blue or purple. Although EABP 1+1 is not comparable to MCF on capacity allocation aspect, it can save significantly amount of energy by shutting nine nonworking nodes down.

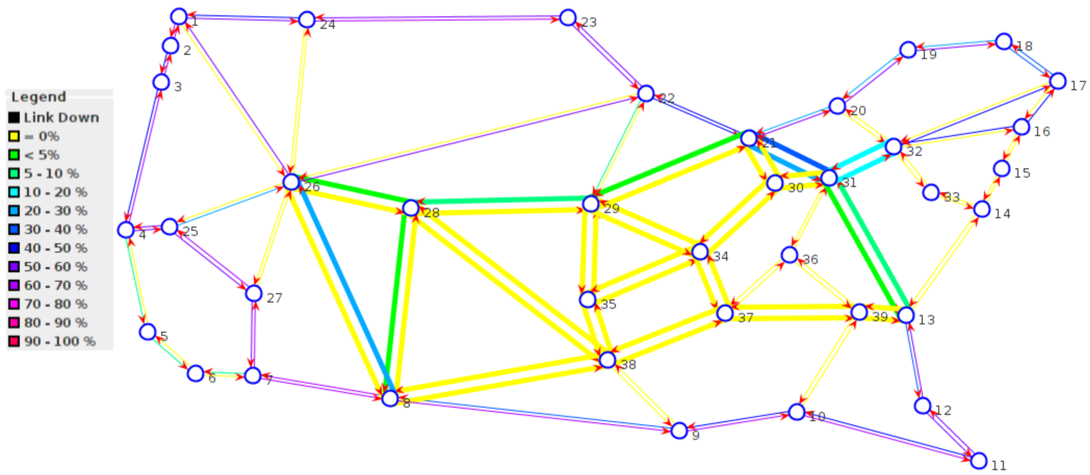


Figure 5.13 Simulation results of EABP 1:1 in the JANOS-US-CA

The result of EABP 1:1's simulation in the JANOS-US-CA network is shown in Fig.5.13. Firstly, we notice that there are 10 nodes could be shut down, which is better than EABP 1+1 and MCF. Secondly, on the edge, its links are in high utilization rate, most of them are over 60% shown as purple colour. The reason is that since the edge nodes are the terminals of traffic demands, which cannot be turned off or switched into sleep, therefore the EABP 1:1 aggregates the traffic flows into these working edge nodes and links. In this topology, EABP 1:1 turned off most of the core nodes and aggregate the backup capacity to the rest core nodes, which could be switched into sleeping mode.

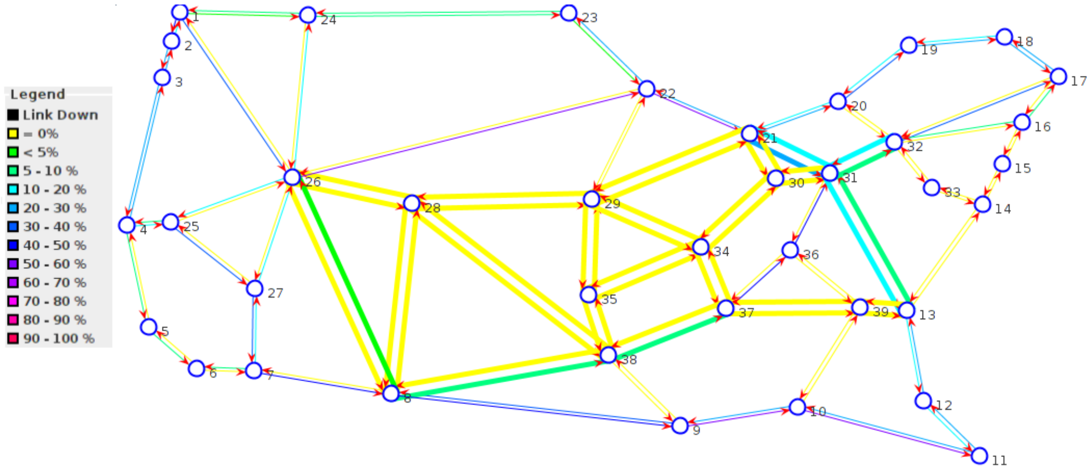


Figure 5.14 Simulation results of EASBP in the JANOS-US-CA

Fig.5.14 shows the results of EASBP algorithm simulating in the JANOS-US-CA topology. It has nine nodes could be shut down. Moreover, compares to EABP 1:1 and EABP 1+1, most of the working links of EASBP has not reached high utilization levels, which reflects EASBP has better performance on lowering links' utilization among our three models.

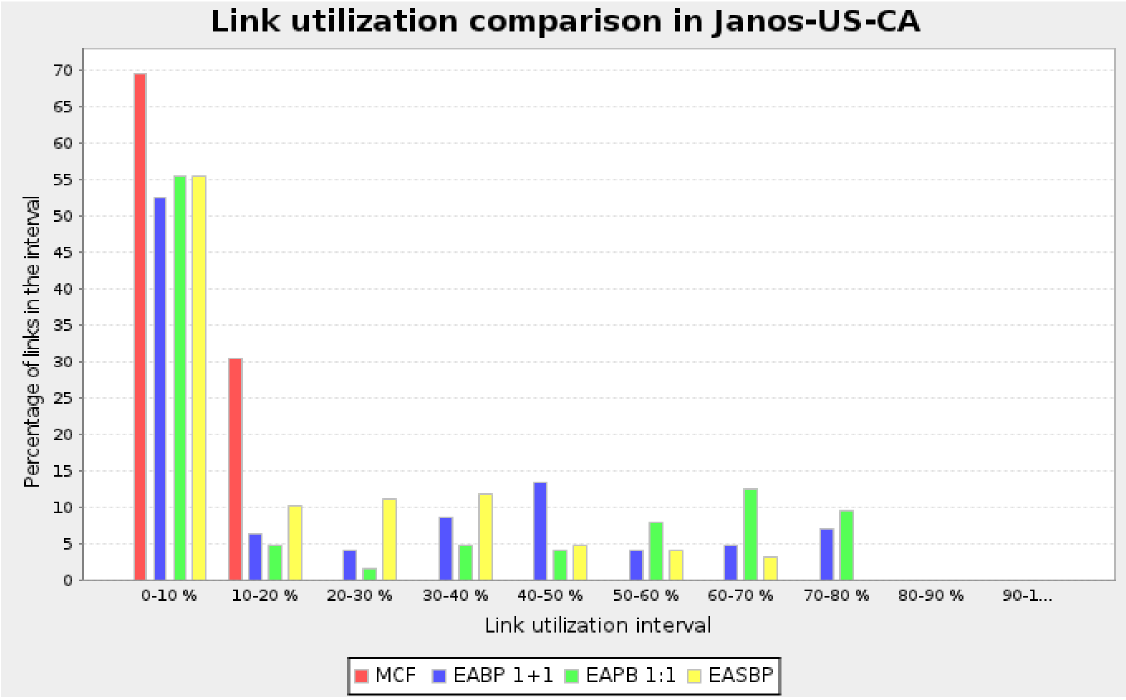


Figure 5.15 Link utilization distribution of the four models in the JANOS-US-CA

Furthermore, we can compare the four algorithms' link utilization performs with the Fig. 5.15 above. It can be seen that the MCF algorithm as the red bars are in the first two utilization intervals, which confirms MCF is sound approach to balance load and thus all links utilization are below 1/5 in the JANOS-US-CA network. As for our three models, the EASBP shown as the yellow bars has less than 10 percent of its links half loaded and no one link reaches utilization of 70%. While the EABP 1+1 model represented in blue bars, nearly one fifth of its links reach 50% utilization or higher. EABP 1:1 shown in green is the worst among the three, more than 30% of its link above 50% utilization. The Fig.5.16 also showed that when links utilization is above 50%, the solid green line which represents the EABP 1:1 is higher than other competitors, while the EABP 1+1 shown in red is in the middle. Moreover, the EASBP (the purple line) is the lowest among our three models when link utilization is over 50%. This finding again confirms that EASBP has better performance on limiting link's utilization compared with EABP 1+1 and EABP 1:1.

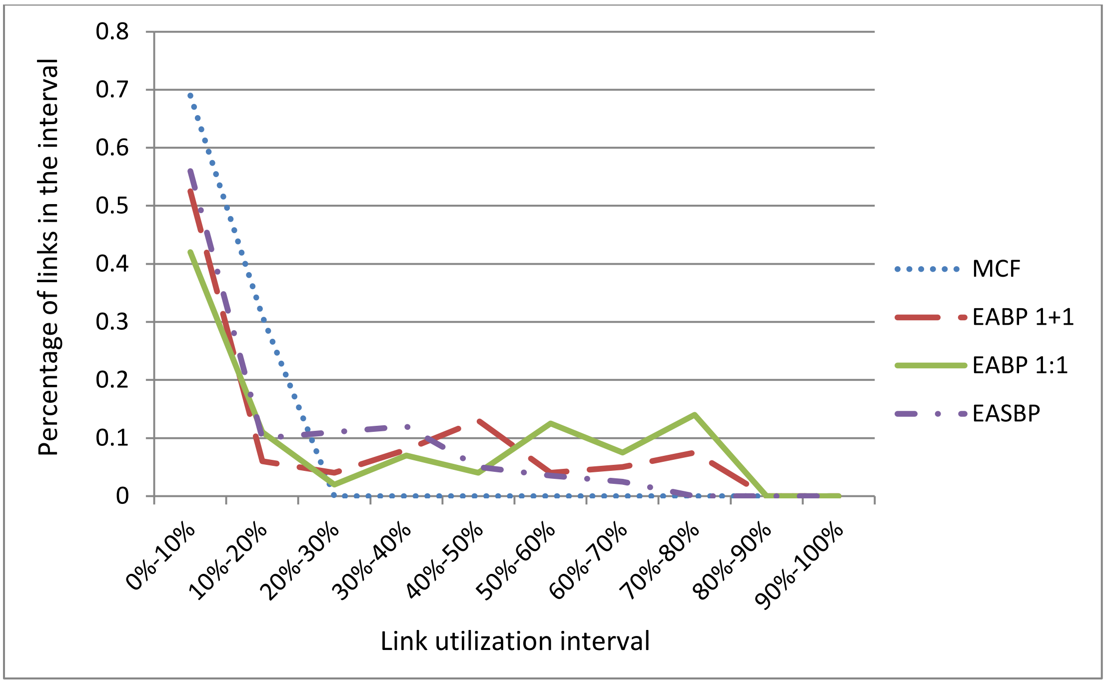


Figure 5.16 Link usage states of the four models in the JANOS-US-CA

In conclusion, the simulation results show that firstly MCF is an advanced algorithm to balance the links' utilization; however it consumes significant more energy because most of network elements are working to share the load, and it does not have backup protection mechanism. Secondly, our models has round 10 unloaded nodes could be turned off to save energy, which means our models are more energy efficient compared with MCF. Moreover, our models apply energy consumption rate strategy and sleeping mode, which will achieve further power reduction. However, none of them is comparable to MCF on balancing links' utilization. Thirdly, EABP 1:1 is the most energy efficient model among the four, because it can switch off more nodes and turn backup resources into sleeping mode. However it has the worst performance of restricting links' utilization due to it tends to aggregate the traffic flows into the already working edge nodes and links. Lastly, the EASBP model is the best one to constraint the link utilization among our three energy aware survivable routing models. It also consumes the least total capacity of network compared with the other two. Therefore, EASBP is better than EABP 1+1 and EABP 1:1 in the aspect of total capacity consumption and to limit links' capacity utilization.

5.2.2 Energy Consumption

In TOTEM, the energy consumption data can be collected from a temporary file which will be created by every run. It is not surprising that the results of AMPL models are very similar as OPL models, because these two programming language have so many in common and both solved by CPLEX solver.

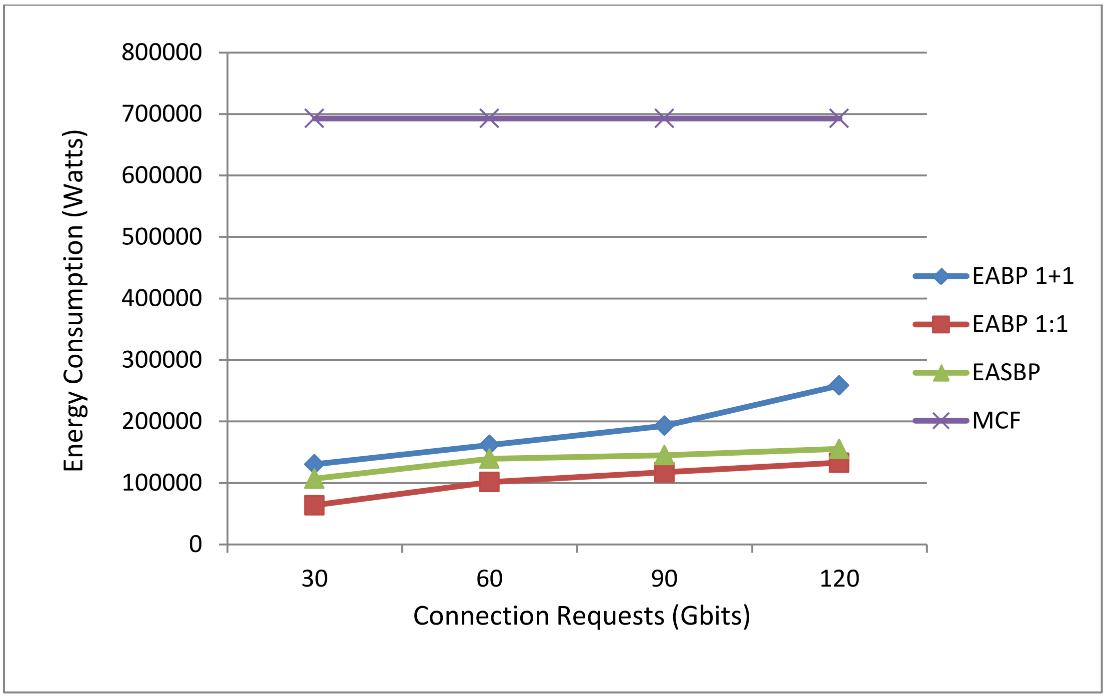


Figure 5.17 Energy consumption of the four models in the COST266

The line chart of Fig.5.17 above offers a graphical view of the total energy consumption of the four models in various demands of traffics in COST266. We assume MCF is like the traditional routing approaches, which energy consumption is independent with traffic loads. It sets every link and node into working status with full power to balance the utilization of devices. Hence, by calculating 28 nodes and 82 links working on full power, we can get the energy consumption of the MCF is 692852 Watts shown as purple line. It can be seen that the MCF algorithm needs far more energy than our models. Especially when connection requests are 30Gbit, EABP 1:1 just consumes around 10% of the amount of the MCF power consumption. Among our models, the EASP 1+1 model, shown as blue line, is always the highest of the three, which means that the EABP 1+1 model consumes more power compared with the other two models.

Moreover, when traffic demands goes over 60Gbit, the green line which represents EASBP is gradually getting close to the red line– the EABP 1:1.

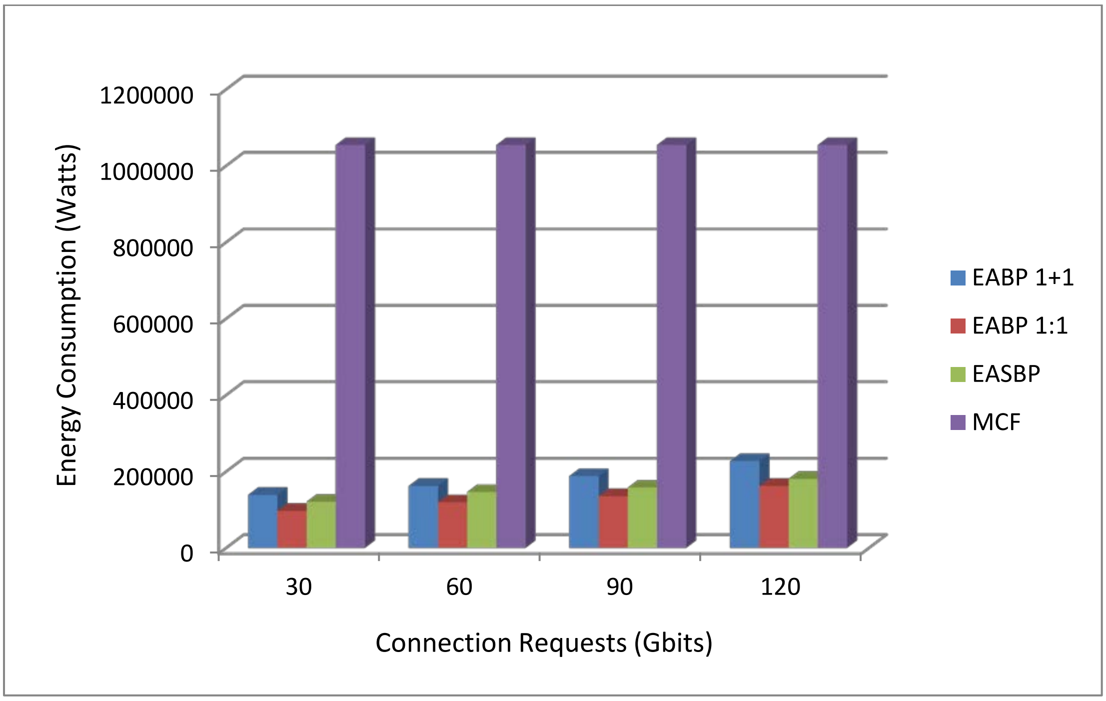


Figure 5.18 Energy consumption of the four models in the JANOS-US-CA

Interestingly, the similar trend can be found in Fig 5.18, which shows the energy consumption results in the JANOS-US-CA network. In this topology, the purple bar, which indicates MCF, needs 1054302.6 Watts (39 nodes and 124 links) to maintain the system. As can be seen from Fig.5.18, when traffic demands are 30Gbit, our models can save most of energy compared with MCF. Especially, our most energy efficient model – EABP 1:1 could save about 90% energy of MCF needed. Then, we noticed that EABP 1+1 model shown as blue bar is the hungriest for power among our three models. In addition, along with the increase of connection requests, there is a trend that the gap of energy consumption between the EABP 1:1(red bar) and EASBP (green bar) is shortened.

Form the findings above, we come to the following three conclusion: Firstly, the MCF is an energy unaware model, which energy expenditures may 10 times more than our models. Secondly, EABP 1+1 is the most energy-hunger model among the three energy aware survivable routing models. Because EABP 1+1 is the only model hasn’t applied sleeping technology, therefore it confirms that sleeping mode is a promising approach to reduce energy cost. Lastly, when traffic demands increases, the value of energy consumption of EASBP will draw near to that of EABP 1:1. In other words, when traffic demands of network is high, the advantage of EABP 1:1 will become less obvious compared with EASBP on energy saving.

5.3 Summary

In this chapter, firstly the process of modifying TOTEM's GUI and integrating our three energy aware survivable routing models are presented. Then the correctness of the three models is tested. Following that, the simulation results of the four algorithms (including MCF) have been analysed. Through the comparison of link utilization and energy expenditure, the MCF algorithm has a significant advantage in lowering system's utilization, but it may need 10 times more energy to sustain compared with our most energy efficient model EABP 1:1. Moreover, it doesn't have sleeping mode, energy scaling strategy, and backup protection. Among our models, EASBP consumes less capacity and has the advantage of limit the links' utilization. Besides, when traffic demands are increasing to large number, the performance of EASBP will comparable to the most energy efficient model -- EABP 1:1 on energy consumption aspect.

Chapter 6

Conclusion and Future work

In this chapter, we firstly summarize our main contributions. Within it, the strengths and limitations of the three proposed energy aware survivable routing models are concluded. Then, we discuss possible future researches on how to improve our models and modify the TOTEM simulator.

6.1 Contributions

The main target of this thesis was to search a possible approach to tackle the trade-off between energy reduction and network survivability in NGNs design. There are three main contributions in this thesis:

Firstly, we propose three energy aware survivable routing algorithms, which not only considering energy reduction, but also taking network survivability into account. In energy saving aspect, we integrate several green technologies into them, such as energy aware routing, sleeping mode, and energy consumption rating strategy. For network survivability concern, EABP 1+1, EABP 1:1, and EASBP are embedded with 1+1 backup protection, 1:1 backup protection, and shared backup protection respectively. In chapter 3, we develop the ILP formulations for each of them.

The second contribution is to implement the ILP models of three routing algorithms in IBM ILOG CPLEX Optimization Studio and solved by the CPLEX 11.1 Solver. By collecting the numerical results, the performance of three routing algorithms are extensively studied and compared. The results show when network is lightly loaded, the most energy efficient model – EABP 1:1 could save up to 90% of energy cost compare with the worst-case MCF algorithm. Because combinational using of energy aware routing, energy consumption rating Strategy and sleeping mode technology. Moreover, the sleeping mode is a promising approach to reduce energy cost, because by applying it, EABP 1:1 can save up to half energy usage than EABP 1+1. However, we believe EASBP could be the best approach to tackle the trade-off between energy reduction and network survivability. This model consumes significantly less capacity but a small increase in energy expenditure, especially under the condition of large traffic demands.

Furthermore, for visualizing the results, we develop and embed the three energy aware survivable routing models into TOTEM simulator. We firstly modified TOTEM's GUI and then integrated our algorithms into it. The simulation results validated our three models' correctness to theory. In addition, by comparing with the MCF algorithm, our models are not so advanced to lowering links' utilization as MCF, but have significant advantages to reduce system's overall energy expenditures and to recovery from network failure. Among our models, EASBP consumes less capacity and has the advantage of limiting the links' utilization. Besides, when traffic demands are increasing to a large number, the performance of EASBP will comparable to the most energy efficient model -- EABP 1:1 on energy reduction aspect.

6.2 Future work

This thesis has initiated an interesting research direction to explore the combined impact on network performance such as network survivability in green networking area. Considering the work covered in this thesis and the development of the future network, it would be useful to highlight some future areas of investigation.

More extensive studies on the optimization between capacity efficiency, energy efficiency in more complex topologies and traffic patterns should be explored. In this research, it is hope to find the relationship among network topology, traffic demand, energy reduction, and network survivability. In other word, for improving our models' advantages, how to modify network topology according to traffic demand, i.e. adding node or link.

Moreover other QoS metric such as delay, control data overhead could be taken into consider for the purpose of network survivability. It is possible to add delay factor into our models ILP formulations.

Further development of TOTEM could be in two aspects: One is to develop an interface to collect the numerical data by other optimization environment such as IBM ILOG Optimization Studio. Therefore, it will save the work of integrate models to TOTEM, and save the computation time. The other is to realize another feature for TOTEM, which can represent nodes and links' energy usage level in different colours.

References

[1] M. Gupta and S. Singh, "Greening of the Internet," in *Proc. the 2003 conf. Applications, technologies, architectures, and protocols for computer communications*, 2003, pp. 19-26.

[2] C. Cavdar, "Energy-efficient connection provisioning in WDM optical networks," in *Optical Fiber Communication Conf.*, 2011.

[3] A. P. Bianzino, *et al.*, "A survey of green networking research," *Communications Surveys & Tutorials, IEEE,* vol. 14, pp. 3-20, 2012.

[4] J. Chabarek, *et al.*, "Power awareness in network design and routing," in *INFOCOM 2008. The 27th Conf. Computer Communications. IEEE*, 2008, pp. 457-465.

[5] B. Luo and W. Liu, "The Sustainability and Survivabiltiy Network Design for Next Generation Cloud Networking," in *Dependable, Autonomic and Secure Computing (DASC), 2011 IEEE 9th Int. Conf.*, 2011, pp. 555-560.

[6] G. Claßen, *et al.*, "Planning wireless networks with demand uncertainty using robust optimization," in *Proc. Int. Network Optimization Conf., INOC*, 2011.

[7] ILOG CPLEX 11.1, http://ilog.com/products/cplex, 2008.

[8] G. Leduc, *et al.*, "An open source traffic engineering toolbox," *Computer Communications,* vol. 29, pp. 593-610, 2006.

[9] M. Webb, "SMART 2020: Enabling the low carbon economy in the information age," *The Climate Group. London,* vol. 1, p. 1.1, 2008.

[10] P. Chowdhury, *et al.*, "Towards green broadband access networks," in *Global Telecommunications Conf., 2009. GLOBECOM 2009. IEEE*, 2009, pp. 1-6.

[11] W. D. Nordhaus, "To slow or not to slow: the economics of the greenhouse effect," *The economic journal,* vol. 101, pp. 920-937, 1991.

[12] D. Pamlin and K. Szomolányi, "Saving the climate@ the speed of light. First roadmap for reduced CO2 emissions in the EU and beyond," *European Telecommunications Network Operators' Association and WWF*, 2006.

[13] N. Wang, *et al.*, "An overview of routing optimization for internet traffic engineering," *Communications Surveys & Tutorials, IEEE,* vol. 10, pp. 36-56, 2008.

[14] C. Lange, "Energy-related aspects in backbone networks," in *Proc.35th European Conf. on Optical Communication (ECOC 2009),(Wien, AU)*, 2009.

[15] K. J. Christensen, *et al.*, "The next frontier for communications networks: power management," *Computer Communications*, vol. 27, pp. 1758-1770, 2004.

[16] C. Cavdar, *et al.*, "Energy-efficient design of survivable WDM networks with shared backup," in *Global Telecommunications Conf. (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1-5.

[17] Y. Agarwal, *et al.*, "Somniloquy: augmenting network interfaces to reduce PC energy usage," in *Proc. 6th USENIX symp. Networked systems design and implementation*, 2009, pp. 365-380.

[18] L. Chiaraviglio, *et al.*, "Reducing power consumption in backbone networks," in *Communications, 2009. ICC'09. IEEE Int. Conf.*, 2009, pp. 1-6.

[19] T. Kelly and S. Head, "ICTs and climate change," *ITU-T Technology, Tech. Rep*, 2007.

[20] L. Chiaraviglio, *et al.*, "Energy-aware networks: Reducing power consumption by switching off network elements," in *FEDERICA-Phosphorus tutorial and workshop (TNC2008) Bruges (Belgium)*, 2008.

[21] *Energy Management: Telecom New Zealand Limited Web Page*, http://www.telecom.co.nz/content/0,8748,203942-203113,00.html.

[22] R. Bolla, *et al.*, "Energy efficiency in the future internet: a survey of existing approaches and trends in energy-aware fixed network infrastructures," *Communications Surveys & Tutorials, IEEE*, vol. 13, pp. 223-244, 2011.

[23] E. Gelenbe and C. Morfopoulou, "Routing and G-networks to optimise energy and quality of service in packet networks," *Energy-Efficient Computing and Networking*, pp. 163-173, 2011.

[24] E. Yetginer and G. N. Rouskas, "Power efficient traffic grooming in optical WDM networks," in *Global Telecommunications Conf., 2009. GLOBECOM 2009. IEEE*, 2009, pp. 1-6.

[25] S. Nedevschi, *et al.*, "Reducing network energy consumption via sleeping and rate-adaptation," in *Proc. the 5th USENIX Symp. Networked Systems Design and Implementation*, 2008.

[26] C. Gunaratne, *et al.*, "Managing energy consumption costs in desktop PCs and LAN switches with proxying, split TCP connections, and scaling of link speed," *Int. Journal of Network Management*, vol. 15, pp. 297-310, 2005.

[27] L. Irish and K. J. Christensen, "A “Green TCP/IP” to reduce electricity consumed by computers," in *Southeastcon'98. Proc. IEEE*, 1998, pp. 302-305.

[28] D. Chen, *et al.*, "Network survivability performance evaluation: a quantitative approach with applications in wireless ad-hoc networks," in *Proc. the 5th ACM*

int. workshop on Modeling analysis and simulation of wireless and mobile systems, 2002, pp. 61-68.

[29] H. Hlavacs, *et al.*, "Energy consumption of residential and professional switches," in *Computational Science and Engineering, 2009. CSE'09. Int. Conf.*, 2009, pp. 240-246.

[30] P. Mahadevan, *et al.*, "A power benchmarking framework for network devices," *NETWORKING 2009*, pp. 795-808, 2009.

[31] G. Ananthanarayanan and R. H. Katz, "Greening the switch," in *Proc. HotPower*, 2008.

[32] D. Meisner, *et al.*, "PowerNap: eliminating server idle power," *ACM Sigplan Notices*, vol. 44, pp. 205-216, 2009.

[33] A. Wierman, *et al.*, "Power-aware speed scaling in processor sharing systems," in *INFOCOM 2009, IEEE*, 2009, pp. 2007-2015.

[34] K. Sabhanatarajan and A. Gordon-Ross, "A resource efficient content inspection system for next generation Smart NICs," in *Computer Design, 2008. ICCD 2008. IEEE Int. Conf.*, 2008, pp. 156-163.

[35] P. Purushothaman, *et al.*, "Power-proxying on the nic: A case study with the gnutella file-sharing protocol," in *Local Computer Networks, Proc. 2006 31st IEEE Conf.*, 2006, pp. 519-520.

[36] M. Jimeno and K. Christensen, "A prototype power management proxy for gnutella peer-to-peer file sharing," in *Local Computer Networks, 2007. LCN 2007. 32nd IEEE Conf.*, 2007, pp. 210-212.

[37] G. Da Costa, *et al.*, "The green-net framework: Energy efficiency in large scale distributed systems," in *Parallel & Distributed Processing, 2009. IPDPS 2009. IEEE Int.Symp.*, 2009, pp. 1-8.

[38] C. Qiao and M. Yoo, "Optical burst switching (OBS)-a new paradigm for an optical Internet," *Journal of high speed networks*, vol. 8, p. 69, 1999.

[39] J. P. Jue and V. M. Vokkarane, *Optical burst switched networks*: Springer, 2004.

[40] L. Chiaraviglio, *et al.*, "Energy-aware backbone networks: a case study," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE Int. Conf.*, 2009, pp. 1-5.

[41] C. Canel, *et al.*, "An algorithm for the capacitated, multi-commodity multi-period facility location problem," *Computers & Operations Research*, vol. 28, pp. 411-427, 2001.

[42] J. Blackburn and K. Christensen, "A simulation study of a new green bittorrent," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE Int.Conf.*, 2009, pp. 1-6.

[43] M. Jimeno, *et al.*, "A network connection proxy to enable hosts to sleep and save energy," in *Performance, Computing and Communications Conf., 2008. IPCCC 2008. IEEE Int.*, 2008, pp. 101-110.

[44] S. Henzler, *et al.*, "Sleep transistor circuits for fine-grained power switch-off with short power-down times," in *Solid-State Circuits Conf., 2005. Dig. Tech.Papers. ISSCC. 2005 IEEE Int.*, 2005, pp. 302-600.

[45] M. Baldi and Y. Ofek, "Time for a "Greener" Internet," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE Int. Conf.*, 2009, pp. 1-6.

[46] A. Bianzino, *et al.*, "Energy-Awareness in Network Dimensioning: a Fixed Charge Network Flow Formulation," in *1st Int. Conf. Energy-Efficient Computing and Networking (e-Energy 2010), Extended Abstract,(Passau, Germany)*, 2010.

[47] A. Kansal and F. Zhao, "Fine-grained energy profiling for power-aware application design," *ACM SIGMETRICS Performance Evaluation Review*, vol. 36, pp. 26-31, 2008.

[48] J. C. C. Restrepo, *et al.*, "Energy profile aware routing," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE Int. Conf.*, 2009, pp. 1-5.

[49] E. Gelenbe and T. Mahmoodi, "Energy-aware routing in the cognitive packet network," in *ENERGY 2011, The 1st Int. Conf. Smart Grids, Green Communications and IT Energy-aware Technologies*, 2011, pp. 7-12.

[50] A. P. Bianzino, *et al.*, "Energy-aware routing: A reality check," in *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, 2010, pp. 1422-1427.

[51] W. Fisher, *et al.*, "Greening backbone networks: reducing energy consumption by shutting off cables in bundled links," in *Proc. 1st ACM SIGCOMM workshop on Green networking*, 2010, pp. 29-34.

[52] M. Allman, *et al.*, "Enabling an energy-efficient future internet through selectively connected end systems," in *6th ACM Workshop on Hot Topics in Networks (HotNets)*, 2007, pp. 1-6.

[53] K. Bilal, *et al.*, "A survey on Green communications using Adaptive Link Rate," *Cluster Computing*, pp. 1-15, 2012.

[54] K. J. Nowka, *et al.*, "A 32-bit PowerPC system-on-a-chip with support for dynamic voltage scaling and dynamic frequency scaling," *Solid-State Circuits, IEEE Journal of*, vol. 37, pp. 1441-1447, 2002.

[55] S. Paget-McNicol, *et al.*, "The Plasmodium falciparum var gene switching rate, switching mechanism and patterns of parasite recrudescence described by mathematical modelling," *Parasitology*, vol. 124, pp. 225-235, 2002.

[56] J. Boch, *et al.*, "The use of a dose-rate switching technique to characterize bipolar devices," *Nuclear Science, IEEE Transactions on*, vol. 56, pp. 3347-3353, 2009.

[57] C. Gunaratne, *et al.*, "Reducing the energy consumption of Ethernet with adaptive link rate (ALR)," *Computers, IEEE Transactions on*, vol. 57, pp. 448-461, 2008.

[58] A. Markopoulou, *et al.*, "Characterization of failures in an IP backbone," in *INFOCOM 2004. Twenty-third Annu. Joint Conf. IEEE Computer and Communications Societies*, 2004, pp. 2307-2317.

[59] S. Balon, *et al.*, "A scalable and decentralized fast-rerouting scheme with efficient bandwidth sharing," *Computer Networks*, vol. 50, pp. 3043-3063, 2006.

[60] K. Kar, *et al.*, "Routing restorable bandwidth guaranteed connections using maximum 2-route flows," *Networking, IEEE/ACM Transactions on*, vol. 11, pp. 772-781, 2003.

[61] M. Kodialam and T. Lakshman, "Minimum interference routing with applications to MPLS traffic engineering," in *INFOCOM 2000. 19th Annu. Joint Conf. IEEE Computer and Communications Societies. Proc.. IEEE*, 2000, pp. 884-893.

[62] M. Kodialam and T. Lakshman, "Dynamic routing of locally restorable bandwidth guaranteed tunnels using aggregated link usage information," in *INFOCOM 2001. 20th Annu. Joint Conf. IEEE Computer and Communications Societies. Proc.. IEEE*, 2001, pp. 376-385.

[63] G. Li, *et al.*, "Efficient distributed path selection for shared restoration connections," in *INFOCOM 2002. 21st Annu. Joint Conf. IEEE Computer and Communications Societies. Proc.. IEEE*, 2002, pp. 140-149.

[64] Q. Chunming and X. Dahai, "Distributed partial information management (DPIM) schemes for survivable networks .1," in *INFOCOM 2002. 21st Annu. Joint Conf. IEEE Computer and Communications Societies. Proc.. IEEE*, 2002, pp. 302-311 vol.1.

[65] D. A. Mello, *et al.*, "A matrix-based analytical approach to connection unavailability estimation in shared backup path protection," *Commun. Lett., IEEE*, vol. 9, pp. 844-846, 2005.

[66] A. M. Koster, *et al.*, "Towards robust network design using integer linear programming techniques," in *Next Generation Internet (NGI), 2010 6th EURO-NF Conf.*, 2010, pp. 1-8.

[67] R. M. Karp, "Reducibility among combinatorial problems," *50 Years of Integer Programming 1958-2008*, pp. 219-241, 2010.

[68] J. Könemann, *et al.*, "From primal-dual to cost shares and back: a stronger LP relaxation for the Steiner forest problem," *Automata, languages and programming*, pp. 105-105, 2005.

[69] M. S. Bazaraa, *et al.*, *Linear programming and network flows* vol. 2: Wiley Online Library, 1990.

[70] S. Ricciardi, *et al.*, "Energy-aware RWA for WDM networks with dual power sources," in *Communications (ICC), 2011 IEEE Int. Conf.*, 2011, pp. 1-6.

[71] A. Vahdat, *et al.*, "Every joule is precious: The case for revisiting operating system design for energy efficiency," in *Proc. 9th workshop on ACM SIGOPS European workshop: beyond the PC: new challenges for the operating system*, 2000, pp. 31-36.

[72] P. Van Hentenryck, *The OPL optimization programming language*, 1999.

[73] G. Pérez Sainz de Rozas and M. A. Garín Martín, "On Downloading and Using CPLEX within COIN-OR for Solving Linear/Integer Optimization Problems," *Biltoki*, 2011.

[74] SNDlib: http://sndlib.zib.de/home.action

[75] T. Van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proc. 1st int. conf. Embedded networked sensor systems*, 2003, pp. 171-180.

[76] J. Lepropre, *et al.*, "Totem: a toolbox for traffic engineering methods," 2006.

[77] R. Fourer, *et al.*, "The AMPL book," ed: Duxbury Press, Pacific Grove, 2002.

[78] B. Fortz and M. Thorup, "Internet traffic engineering by optimizing OSPF weights," in *INFOCOM 2000. 19th Annu. Joint Conf. IEEE Computer and Communications Societies. Proc.. IEEE*, 2000, pp. 519-528.

[79] S. Balon, *et al.*, "Traffic engineering an operational network with the TOTEM toolbox," *Network and Service Management, IEEE Transactions on*, vol. 4, pp. 51-61, 2007.

[80] S. Uhlig, *et al.*, "Providing public intradomain traffic matrices to the research community," *ACM SIGCOMM Computer Communication Review*, vol. 36, pp. 83-86, 2006.

[81] I. Iliadis and D. Bauer, "A new class of online minimum-interference routing algorithms," *NETWORKING 2002: Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications*, pp. 959-971, 2006.

Appendix A: OPL + CPLEX Optimization Environment

OPL + CPLEX is a popular and powerful combination to solve optimization problems. In our case study, we firstly use Optimization Programming Language to model the three energy aware survivable routing algorithms of previous chapter. Then the three models are solved in IBM ILOG CPLEX Optimization Studio.

OPL

Optimization Programming Language (OPL) is a modelling language for describing (and solving) optimization problems. The motivation for using modelling languages to model optimization problem is primarily due to two reasons:

(a). It provides a syntax that is close to the mathematical formulation, thus making it easier to make the transition from the mathematical formulation to something that can be solved by the computer.

(b). It enables a clean separation between the model and the accompanying data. The same model can then be solved with different input data with little extra effort.

OPL is just one example of a modelling language. Other examples include AMPL, Mosel and GAMS. Modelling languages are typically used for linear and integer optimization problems, but it is also possible to formulate quadratic problems in OPL.

A typical OPL model includes the following four parts:

1. Data declarations. This part declares the data parameters used in the model, typically coefficients and index sets for the decision variables.
2. Decision variables. These are declared with the keyword *dvar*.
3. Objective function. The objective function is declared with the keyword *minimize* or *maximize* depending on what you want to do.
4. Constraints. The constraints are declared using the keyword *subject to*.

A simple OPL model could be as follows:

```
dvar float x;
dvar float y;
minimize
```

```
4*x – 2*y;
subject to {
x – y >= 1;
x >= 0;
}
```

The above model solves the linear optimization problem:

minimize 4x -2y

subject to x-y>=1

x>=0

OPL provides an easy approach to express ILP problem. The objective of our three energy aware survivable routing models is to minimize the energy usage under a series of constraints. The following are a fraction of our OPL codes, the comments are after the symbol "//".

```
int NumNodes = ...;   // Number of nodes
range N = 1..NumNodes;
int NumArcs = ...;   // Number of arcs
range R = 1..NumArcs;
{arc} Arcs = ...; // Get the set of arcs
{nodes} Nodes = ...;// Get the set of nodes
{traffics} Traffics = ...;// Get the set of traffics
float vol[Traffics] = ...;// Get the volumes of each traffic
...
dvar float+ Arcs_Flow[a in Arcs][Traffics] in 0..a.capacity; // Primary path in Arc a for Traffic t
dvar float+ Arcs_BackupFlow[a in Arcs][Traffics] in 0..a.capacity;// Backup path in Arc a for Traffic t
dvar float+ primary_link_comsuption; // The energy consumption for total of links in primary path
dvar float+ primary_node_comsuption; // The energy consumption for total of nodes in primary path
dvar float+ backup_comsuption;  // The energy consumption for total of links and nodes set as backup state
dvar boolean x[N];//Switch for Nodes. x=1, node on; x=0, node off.
dvar boolean y[R];//Switch for Arcs.  y=1, arc  on; y=0, are  off.
```

```
dvar boolean Node_Z[N];//sleep for Nodes
dvar boolean Arc_Z[R];//sleep for Arcs
...
minimize
  primary_link_comsuption + primary_node_comsuption +  backup_comsuption;
                                  // the overall system energy expenditure
subject to {
primary_link_comsuption == sum(a in Arcs)(l_arc[a] + y[a.id] *
a.minimum_comsuption);      // calculate the primary links energy consumption

primary_node_comsuption ==  sum (n in Nodes) (k_node[n] + x[n.id] *
n.minimum_comsuption);      // calculate the primary nodes energy consumption

backup_comsuption == sum(a in Arcs,t in Traffics)(Arc_Z[a.id]*a.idle_energy)+sum (n
in Nodes)(Node_Z[n.id]*n.idle_energy);
//calculate the energy consumption of backup links and nodes

     forall(i in N, t in Traffics)     // search for primary path
       {
         sum(a in Arcs: i == a.fromnode) Arcs_Flow[a][t]
            - sum(a in Arcs: i == a.tonode) Arcs_Flow[a][t]
             == Tag[i][t]*vol[t];
        }

    forall(i in N, t in Traffics)   // search for backup path
       {
         sum(a in Arcs: i == a.fromnode) Arcs_BackupFlow[a][t]
            - sum(a in Arcs: i == a.tonode) Arcs_BackupFlow[a][t]
             == Tag[i][t] *vol[t];
        }
    forall(a in Arcs,t in Traffics)  // disjoint primary path and backup path
         {
           Arcs_Flow[a][t] +  Arcs_BackupFlow[a][t]<= vol[t];
          }
```

```
    ...
}
```

The above codes mainly about how our models search for primary links and backup links, and restrict primary path and backup path are disjointed. It firstly gives the parameters and decision variables. Then we can see the object of this model is to minimize the total energy consumption, which includes the energy usage of links and nodes in primary path as well as that of backup links and nodes. Lastly, in the constraints part, it shows how primary links and backup links can be found. Moreover, for a traffic flow, its primary path and backup path cannot have an overlapped link. The last constraint is in the purpose of separate them. This is only part of our models for demonstration. The OPL codes of the three models are in the DVD disk attached to the thesis.

IBM ILOG CPLEX Optimization Studio

IBM ILOG CPLEX Optimization Studio is a consolidation of the OPL integrated development environment (IDE) and the CPLEX and CP Optimizer solution engines in a single product. CPLEX Optimization Studio provides the fastest way to build efficient optimization models and state-of-the-art applications for the full range of planning and scheduling problems. With its integrated development environment, descriptive modelling language and built-in tools, it supports the entire model development process. CPLEX, a feature of IBM ILOG Optimization Studio, offers state of the art performance and robustness in an optimization engine for solving problems expressed as mathematical programming models.

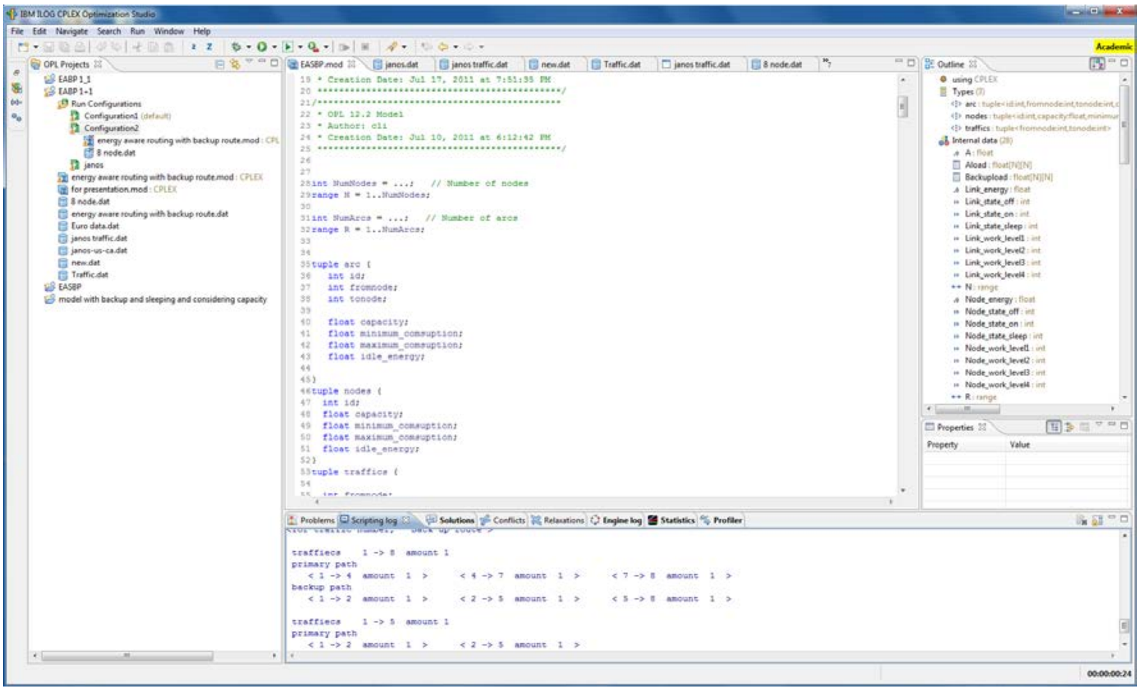


Figure 6.1 GUI of IBM ILOG CPLEX Optimization Studio

Fig.6.1 shows the GUI of CPLEX Optimization Studio. It is divided into four main areas: 1. OPL projects have been set up in the left hand side; 2. the centre is where we place OPL programs; 3. the right hand side lists all the variables and their type; 4. the experimental result can be obtained from the bottom.

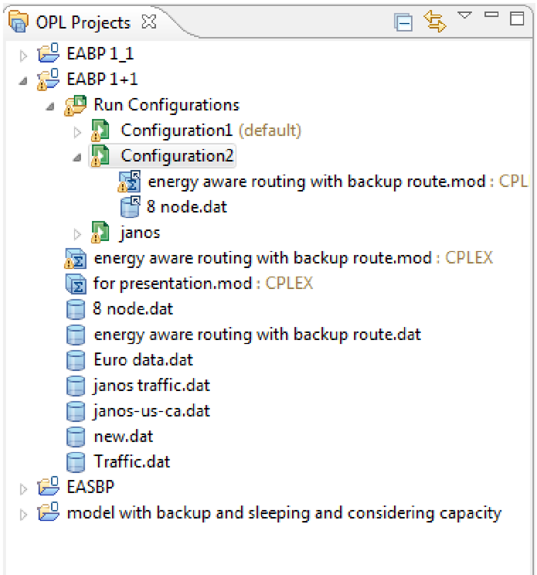


Figure 6.2 OPL Projects Window of CPLEX Optimization Studio

There are two features need to introduced in details. Fig.6.2 above shows the OPL project window, each fold is an existing OPL project. There are two types of file, one is .mod and the other is .dat, which represent model and data respectively. In this studio, model and data are independent. One model can be tested by different data set in quite easy way. In other words, our three energy aware survivable routing models can be validated by different topologies and traffic loads.

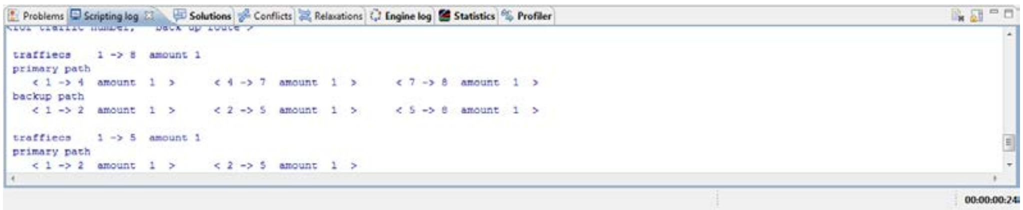


Figure 6.3 Script Log Window of CPLEX Optimization Studio

The experimental resulted can be checked in Script Log Window (Fig 6.3), such as energy expenditure, bandwidth usage, working level of network elements. Moreover, we also wrote some code to print out both primary path and backup path of every traffic demand. In this way, the route of traffics can be traced.

Appendix B: Background on AMPL and TOTEM

In the previous chapter, the performance of our three energy aware survivable routing models was compared, however only through the numerical results produced by IBM CPLEX Optimization studio. Although OPL + CPLEX is convenient to model and operate, it cannot provider a visual result of how models routing the traffic flows. Therefore, we found TOTEM to simulate our results. TOTEM is an open source simulator, so that we can modify some of its feature for experimental purpose. By using AMPL, which is a modelling language very similar to OPL, we integrate EABP 1+1, EABP 1:1, and EASBP into TOTEM.

AMPL

AMPL [77], an acronym for "A Mathematical Programming Language", is an algebraic modelling language for describing and solving high-complexity problems for large-scale mathematical computation (i.e. large-scale optimization and scheduling-type problems). AMPL is a powerful language designed specifically for mathematical programming; it has a variety of features and options. Firstly, AMPL is available for many popular 32- and 64-bit platforms including Linux, Mac OS X and Windows. Secondly, AMPL supports a wide range of problem types, such as linear programming, mixed-integer programming, nonlinear programming, and mixed-integer nonlinear programming. Thirdly, AMPL supports dozens of modern solvers, both open source and commercial, including CPLEX, CBC. Fourthly, AMPL allows separation of model and data, which support re-use and simplify construction of large-scale optimization problems. Last by not least, one particular advantage of AMPL is the similarity of its syntax to the mathematical notation of optimization problems. This allows for a very concise and readable definition of problems in the domain of optimization.

In general, an AMPL model has three main parts: Part 1 is declaration of variables (variable, parameters, sets etc.); Part 2 is objective function, which usually is maximize or minimize plus a mathematical expression; all the constraints go to Part 3, it including constraint's name and corresponding mathematical expression. The following is a simple AMPL example:

```
# Part 1 declaration of variables
var float x;
var float y;
# Part 2 objective function: name and mathematical expression
Minimize target :  4*x – 2*y;
# Part 3 constraints: name and mathematical expression
subject to  constraint1 : x – y >= 1;
subject to  constraint2 : x >= 0;
```

The above model solves the linear optimization problem:

minimize 4x -2y

subject to x-y>=1

x>=0

There are some comments need to mention:

1. The symbol # indicates the start of a comment.
2. Variables must be declared using the var command.
3. All lines of code must end with a semi-colon (;).
4. The objective function starts with the command maximize or minimize, followed by the name of the objective function, followed by a colon (:) which is finally followed by the function that should be optimized, terminated by corresponding semicolon.
5. Each constraint or array of constraints starts with the command subject to followed by a name, followed by a colon (:) and finally followed by the corresponding logical constraint.
6. Names are unique. Variables, constraints and objective function must have different names.
7. AMPL is case sensitive. Commands must be in lower case.

TOTEM only accept the model written by AMPL, therefore we program the three models by AMPL so that they can be integrated into TOTEM. The following codes demonstrate part of our models. The comments for each of them are after the #.

```
# ***********************
# SETS
# ***********************
```

```
set VERTICES;      # set of vertices of the network
set LINKS;         # set of links of the network
# **********************
# PARAMETERS
# **********************
param InLinks{i in VERTICES, j in LINKS} default 0; # links entering the node
param OutLinks{i in VERTICES, j in LINKS} default 0; # links leaving the node
param Capa {l in LINKS} default 0; # capacity of links
param Demand {i in VERTICES, j in VERTICES} default 0;  # traffic demand
  between nodes i and j
# **********************
# VARIABLES
# **********************
var primary_flow {l in LINKS, i in VERTICES, j in VERTICES} >= 0;
var backup_flow {l in LINKS, i in VERTICES, j in VERTICES} >= 0;
var utilization {l in LINKS} >= 0;
var node_utilization {i in VERTICES} >= 0;

var x{l in LINKS, i in VERTICES, j in VERTICES} binary; # primary link switch
var y{l in LINKS, i in VERTICES, j in VERTICES} binary; # backup link switch

var z{i in VERTICES} binary;  # working node
var z1{i in VERTICES} binary; # sleeping node

var link_energy{l in LINKS} >= 0; # link total energy
var node_energy{i in VERTICES} >= 0; # node total energy

...

# **********************
# OBJECTIVE FUNCTION
# **********************
```

```
minimize cost: sum{l in LINKS}link_energy[l] + sum{i in VERTICES}
node_energy[i];

# **********************
# CONSTRAINTS
# **********************

########   Path searching
# Search for Primary Path
subject to primaryFlowConservationC{k in VERTICES, i in VERTICES, j in
VERTICES}:
    (sum{l in LINKS} primary_flow[l,i,j] * OutLinks[k,l]) - (sum{l in LINKS}
    primary_flow[l,i,j] * InLinks[k,l]) = (if (k = i) then Demand[i,j] else (if (k=j)
    then -Demand[i,j] else 0));

# turn on primary links       x is the switch 1—on ; 0 –off
subject to primary_link_switchC{l in LINKS, i in VERTICES, j in VERTICES}:
      primary_flow[l,i,j] <= x[l,i,j] *  Capa[l];

# Search for Backup Path
subject to backupFlowConservationC{k in VERTICES, i in VERTICES, j in
VERTICES}:
    (sum{l in LINKS} backup_flow[l,i,j] * OutLinks[k,l]) - (sum{l in LINKS}
    backup_flow[l,i,j] * InLinks[k,l]) = (if (k = i) then Demand[i,j] else (if (k=j)
    then -Demand[i,j] else 0));

# turn on backup links          y is the switch 1 means in backup state ;
subject to backup_link_switchC{l in LINKS, i in VERTICES, j in VERTICES}:
   backup_flow[l,i,j] <= y[l,i,j] *  Capa[l];

# primary link and backup link must be disjointed
subject to disjointNessC{l in LINKS, i in VERTICES, j in VERTICES}:
x[l,i,j] + y[l,i,j] <= 1;
```

```
...
end;
```

The above AMPL codes show how the model set primary links and backup links for traffic demands. In the beginning, the data parameters and decision variables are given. Following that, the object of the model is presented, which is to minimize the energy cost both nodes and links. The last part is the constraint. By applying them all, traffic flows' primary path and backup path can be found. In addition, the last constraint makes sure primary path and backup path are disjointed. This is just a small fraction of our AMPL models. The whole codes of the three modes have copied in the attached DVD disk.

Overview of TOTEM

Research in the traffic engineering [78] field has been carried out for years and some solutions exist, but few of these are actually used by operators to manage their network. One reason is that these methods are specifically implemented for research and simulation purposes. It is considered difficult to integrate these methods in an operational environment. The main objective of the TOTEM toolbox ([79-80]) is to reconcile the academic and the operational worlds by providing interoperable and user-friendly interfaces with existing tools. This toolbox can also be used by academic researchers who want to test, compare and promote their own research works.

TOTEM stands for TOolbox for Traffic Engineering Methods, which is a Java based open source software. It has three main advantages listed below:

- Has standard and popular traffic engineering algorithm library, which includes MCF, IGP, IGP-WO, Shortest path etc. It is also combined in a common framework, and makes it possible to test and evaluate several traffic engineering solutions quickly.
- User-friendly GUI, the routing result can be showed in diagram, and also different link's utilization can be presented in different color.
- It is open source software and also provides the developing space for new algorithms, which make us able to integrate new Green and BlueGreen routing algorithms.

The design of the toolbox also allows different utilization modes. It can be deployed either as an on-line tool in an operational network [81] or as an off-line traffic engineering simulator [61]. Moreover, a large variety of traffic engineering methods are integrated. These methods can be classified with respect to different axes like intradomain or interdomain, on-line or offline, IP or MPLS (Multi Protocol Label Switching), centralized or distributed.

In this thesis, we have investigated TOTEM, so as to implement, test and validate our new algorithms developed previously in IBM ILOG Optimization Studio. The reason for this transition is that, the previous ILOG tool is a pure mathematical optimization package can solve the ILP problems, while it is not a network simulator and cannot show network-oriented performance. We are expecting that we can study the energy aware traffic engineering algorithm's behaviours and also their relationship to the underlie network structure. The TOTEM toolbox provides us much potential to simulate our three models and also verify them under various 'what-if' network scenarios.

A new proposed TE method can be implemented into TOTEM because the TOTEM provides an open source and scalable platform to integrate new algorithms. It also has benefit that the presence of other existing and standard methods as benchmarks to ours for comparison and validating purposes. Moreover Totem can also provide other network simulation support, such as topology/traffic generating, and simulation results analysis, and it also contain a repository of existing topologies and traffic matrices abstracted from real world network topologies and traffic database.